a. The treatment capacity required for treatment alone (Figure 4-6a) is given by the equation of the isoquant curve

$$T = T_1 + (T_2 - T_1)e^{-KS} \quad [3, p\ 38]$$

with storage S set to zero, namely $T = T_2$. Values of T_2 were previously computed in Step 4. The cost of this wet-weather treatment capacity is obtained by multiplying T_2 by the unit cost, \$15,000/Mgal·d (Step 3).

See Table 4-3 for results. The values in parentheses after the costs in Table 4-3 are the ratios of the costs to the respective case (a) costs.

TABLE 4-3. SUMMARY OF COSTS OF ALTERNATIVE INTEGRATION METHODS

Pollutant removal, R_1, %	10	25	50	75
Secondary treatment efficiency, η	0.85	0 85	0.85	0.85
Runoff control, R, %	11.8	29 4	58.8	88.2
Cost of treatment alone (case a), $\$10^6$/yr	0.22 (1.00)[a]	0.45 (1.00)	1 37 (1.00)	4.25 (1.00)
Cost of integrated wet- and dry-weather treatment (case b), $\$10^6$/yr	0.11 (0.50)[a]	0 34 (0.76)	1 26 (0.92)	4.13 (0 97)
Cost of integrated wet-weather storage and treatment (case c), $\$10^6$/yr	0 075 (0.34)	0 145 (0 32)	0.370 (0 27)	0 945 (0.22)
Cost of fully integrated storage and treatment (case d), $\$10^6$/yr	0 050 (0.23)	0.090 (0 20)	0.261 (0 19)	0 836 (0 20)

a Values in parentheses are the ratios of the costs to the respective case (a) costs.

b. When the wet- and dry-weather treatment facilities are integrated (Figure 4-6b), the flow to be processed by wet-weather treatment is reduced by one dry-weather flow (Assumption 6), or 7.29 Mgal/d (Step 5a). Therefore, the cost of the reduced wet-weather treatment facility is the case (a) cost less

7.29 (Mgal/d) 15,000 (\$/Mgal·d) = \$109 350

See results in Table 4-3.

c. The costs of optimized, integrated wet-weather treatment and storage are obtained directly from Figure 4-3.

See results in Table 4-3.

d. The costs of wet-weather treatment integrated with both wet-weather storage and dry-weather treatment are the same as for case (c), but reduced by the value of the treatment provided in the dry-weather plant. This reduction will be \$109 350 (Step 6b) or the cost of secondary treatment alone (Figure 4-4), whichever is the lesser.

See Table 4-3 for results.

The alternative costs of Table 4-3 are compared graphically in Figure 4-7.

Comments

1. A further University of Florida assumption, on the amount of on-site stormwater storage capacity provided, has not been made here. When this capacity must be limited below the requirements of Figure 4-3, optimal costs for cases (c) and (d) of Step 6 will rise.
2. The cost-effectiveness trade-off procedure of Step 5 compares the cost of extending secondary dry-weather treatment to tertiary with the incremental cost per pound BOD removed (\$0.65 in this case) at wet-weather removal efficiency R_1, rather than with the overall cost per pound (\$1.91). The former comparison overlooks the significant cost (with this method) of providing a negligible BOD removal capability (Figure 4-4). The potential user is advised to use the Step 5 procedure only with the fullest understanding of the principles involved.
3. In Step 6, the significantly lower costs of integration alternatives (c) and (d) are benefitting from a very low unit annual cost for storage (0.016 \$/gal; Step 3). This cost could equally well be one to two orders of magnitude higher. With a tenfold increase in unit storage cost, for 75% runoff control and secondary wet-weather treatment for example, the optimal storage capacity is reduced by 81% (to 4.78 Mgal); the optimal treatment capacity is increased by 670% (to 101.7 Mgal/d); and the optimal total annual cost is increased by 272% (to \$2 296 000). This is then practically as high as the case (b) annual cost (Figure 4-7).

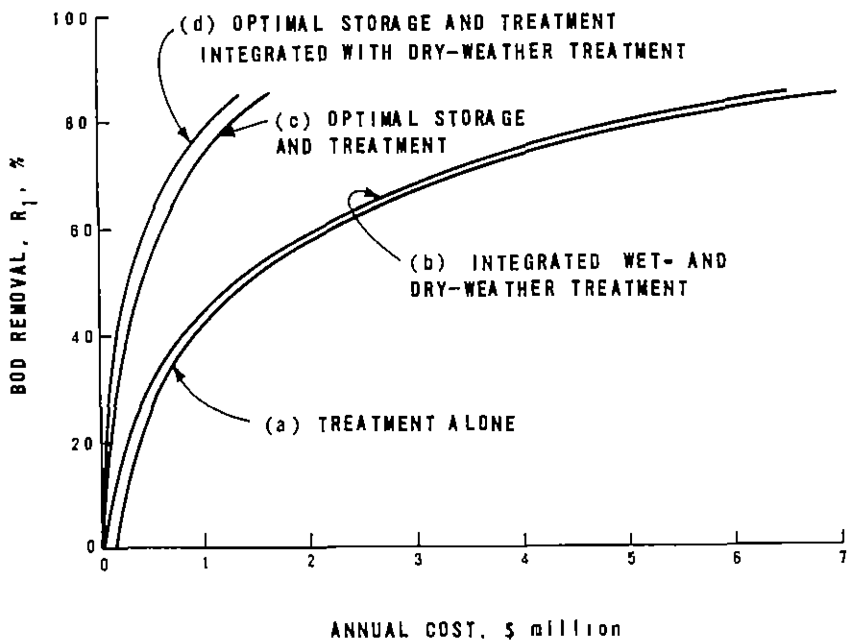

Figure 4-7. Variation of costs of various integration methods with BOD removal.

EXAMPLE PROBLEM 4-4: SELECTION OF A DESIGN STORM FROM THE HISTORICAL RECORD

Select design storms for the basin, using (a) the Simplified SWMM rainfall characterization procedure [9, Section VI] and (b) a modification of the Boston (EMMA [35]) synthetic hyetograph development procedure.

Specified Conditions

1. Period of rainfall record: 1/2/1907-9/30/1976 (69.75 years).

2. Rainfall amounts: hourly rainfall increments, recorded to the nearest 0.01 in., at a base rain gage within or adjacent to the study area.

Assumptions

1. An independent storm event is identified by preceding and following dry periods of at least 6 hours duration.

2. For the modified Boston procedure (b), a synthetic hyetograph with a 1 year return period is preferred for the reasons given in [35, Appendix B].

Solution

1. Acquire the appropriate hourly precipitation tape file from the National Oceanic and Atmospheric Administration (previously the U.S. Weather Bureau), Environmental Data Service, in Asheville, N.C. Print the entire historical record.

2. Using the computer program EVENT [9, Section VI], define the independent storm events using Assumption 1. Using program LISTSQ [9, Section VI], tabulate these storms with event characteristics such as: date, starting hour, duration, total precipitation, maximum hourly rainfall and the hour in which it occurred, and elapsed days since the previous storm.

3. Using an IBM package sorting program, SORT [9, Section VI], rank the N storms with the largest total precipitation, where N = 1.5 x number of years of rainfall record. In this case N = 1.5(69.75) = 105 storms. Use program LISTRK [9, Section VI], to list the ranked files.

4. Determine the average intensity (total precipitation/storm duration) for each of the N storms in Step 3. Apply programs SORT and LISTRK a second time, to rank and list the storms by average intensity. Select for further consideration the upper 50% of this ranking, containing the larger average intensities. These will be the storms that generally place the greatest stress on the storage/treatment facilities.

5. Apply programs SORT and LISTRK a third time to rank and list the remaining storms by duration. Results are presented in Table 4-4. Identify the mean and median durations; these, from Table 4-4, are:

   Mean duration: 30.34 h
   Median duration: 30.00 h

6. Select from the Step 5 ranking about 10 storms with durations in the neighborhood of the mean and/or median, and, if possible, having similar shape characteristics (time to peak, time distribution of rain). The 17 storms selected for the study area are indicated by shading in Table 4-4 (duration ranks = 17 to 30). Tabulate, from Step 1, the hourly rainfall for each; results are given in Table 4-5.

7. To complete the Simplified SWMM rainfall characterization procedure (a), select from the storms of Step 6 that one (those) which is (are) judged to be most representative of them all, to be the design storm(s).

   Due to the variety of rainfall distributions at the study area (Table 4-5), two storms, labeled S1 and S2 in Tables 4-4 and 4-5, were selected as being representative. Their hyetographs are plotted in Figure 4-8.

TABLE 4-4. STEP 5 RESULTS OF STORM EVENT RANKING

Year	Month	Day	Start hour	Duration Hours	Duration Rank	Total rainfall Inches	Total rainfall Rank	Average intensity, in./h	Maximum hour rainfall Amount, in.	Maximum hour rainfall Hour after start	Days since last storm	Selection
1945	12	26	24	56	1	3.76	7	0.067	0.36	11	0	
1956	1	13	15	50	2	4.70	2	0.094	0.48	24	3	
1908	2	1	1	43	3	3.04	20	0.071	0.15	1	3	
1967	1	20	5	42	4	4.55	3	0.100	0.41	39	9	
1914	2	19	14	39	5	2.98	23	0.076	0.32	13	0	
1916	1	2	8	39	5	3.67	10	0.094	0.40	16	1	
1943	1	19	24	39	5	3.02	22	0.077	0.35	35	22	
1942	11	16	12	38	8	3.10	18	0.082	0.27	10	1	
1958	4	1	18	38	8	2.64	37	0.069	0.95	20	0	
1916	1	12	20	37	10	2.53	42	0.068	0.51	32	2	
1973	1	8	4	37	10	3.25	16	0.088	0.45	13	12	
1950	1	16	4	36	12	2.81	29	0.078	0.31	18	2	
1910	11	17	18	35	13	2.32	55	0.066	0.45	17	2	
1924	12	20	18	35	13	3.58	12	0.102	0.56	20	4	
1950	12	2	12	34	15	2.58	40	0.076	0.26	14	2	
1921	12	25	21	33	16	2.26	57	0.068	0.29	27	0	
1908	1	19	24	32	17	2.18	63	0.068	0.26	19	0	
1911	1	13	9	32	17	2.40	39	0.081	0.46	9	0	
1919	2	8	24	32	17	3.72	8	0.116	0.43	11	0	
1926	4	4	3	32	17	2.70	34	0.084	0.39	7	17	
1940	2	26	8	32	17	2.73	31	0.085	0.24	30	0	
1946	1	31	19	32	17	2.70	35	0.084	0.26	13	0	
1969	10	14	15	32	17	2.36	53	0.074	0.47	20	4	S1
1926	1	30	13	31	24	2.49	45	0.080	0.21	13	1	
1958	2	18	3	31	24	2.16	69	0.068	0.29	17	1	
1931	12	26	12	30	26	2.81	28	0.094	0.33	21	3	
1962	10	12	17	30	26	3.34	15	0.111	0.63	2	0	
1936	2	10	18	29	28	3.18	17	0.110	0.47	16	9	S2
1940	3	29	15	29	28	3.86	6	0.133	0.28	3	0	
1907	3	18	4	28	30	1.92	103	0.069	0.20	10	1	
1937	1	30	18	28	30	2.04	87	0.073	0.24	10	5	
1941	12	27	20	28	30	2.08	84	0.074	0.76	21	0	
1952	12	19	1	28	30	2.10	76	0.075	0.41	21	8	
1915	3	27	10	27	34	1.95	99	0.072	0.27	2	0	
1921	1	16	12	27	34	2.70	33	0.100	0.39	18	4	
1968	3	22	19	27	34	2.53	43	0.094	0.39	9	0	
1937	3	20	23	26	37	1.94	100	0.075	0.30	8	0	
1969	12	19	6	26	37	3.03	21	0.117	0.73	23	0	
1923	4	3	22	25	39	2.06	82	0.082	0.33	18	1	
1972	11	13	4	25	39	2.48	47	0.099	0.51	21	3	
1912	3	4	23	24	41	2.09	78	0.087	1.05	9	0	
1962	2	14	8	24	41	1.92	105	0.080	0.48	4	1	
1970	1	20	14	24	41	2.31	56	0.096	0.25	4	0	
1953	4	26	14	23	44	2.36	52	0.103	0.40	14	7	
1973	11	5	11	23	44	2.72	32	0.118	0.35	5	14	
1941	3	30	8	22	46	2.22	61	0.101	0.40	10	0	
1915	12	2	23	21	47	3.40	14	0.162	0.36	12	0	
1920	12	23	6	21	47	2.02	89	0.096	0.30	19	2	
1959	9	17	21	21	47	2.06	85	0.098	0.48	13	24	
1913	11	18	2	20	50	2.21	62	0.110	0.33	9	5	
1922	11	6	7	20	50	2.09	79	0.104	0.35	17	6	
1926	1	28	5	19	52	2.38	48	0.125	0.37	19	11	
1952	12	6	17	16	53	1.92	104	0.120	0.38	8	1	

TABLE 4-5. HOURLY RAINFALL (IN HUNDREDTHS OF AN INCH) FOR STORMS SELECTED IN STEP 6

Storm hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Selection
Date																																	
01/19/1908	1	6	8	11	7	9	7	1	1	0	1	1	0	5	3	10	16	18	26	22	22	12	11	7	5	1	1	0	1	0	1	4	
01/13/1911	2	5	8	10	9	7	7	22	46	19	7	7	6	11	4	3	6	7	5	10	10	6	7	19	6	3	1	1	1	2	1	2	
02/09/1919	1	0	1	11	17	11	2	5	13	17	53	32	24	9	13	16	20	7	3	0	1	11	3	7	10	11	35	11	4	12	2	10	
04/04/1926	7	4	3	5	10	13	39	22	15	6	0	0	1	1	0	0	1	0	1	22	31	8	13	4	10	16	1	4	24	5	3	1	
02/26/1940	3	1	4	4	2	6	10	9	9	16	7	9	11	20	17	13	16	18	8	1	2	2	22	1	0	4	1	4	8	24	11	10	
01/31/1945	4	2	0	1	12	18	2	16	23	16	25	12	4	8	16	9	5	7	0	0	1	19	6	10	13	4	1	0	11	7	17	1	
10/14/1969	1	0	0	1	0	0	0	1	2	3	2	5	5	4	8	7	27	24	35	47	5	1	2	16	14	25	0	0	0	1	0	1	S1
01/30/1926	4	15	14	13	20	16	4	2	0	1	4	5	21	19	21	20	14	6	1	11	9	0	1	10	0	0	1	0	16	0	1		
02/18/1958	2	3	6	12	5	5	10	6	11	1	2	20	1	7	12	2	29	21	7	11	2	1	1	4	1	2	3	4	22	1	1		
12/26/1931	2	2	5	2	0	1	5	4	10	13	17	17	9	9	8	28	21	13	21	19	33	11	2	2	6	5	2	8	5	1			
10/12/1962	10	63	21	20	11	15	9	5	10	9	10	10	14	9	16	9	4	10	7	7	5	14	5	8	0	1	1	17	3	1			
02/10/1936	2	11	30	12	12	26	23	3	30	13	4	1	21	6	2	47	18	26	9	2	0	0	0	0	11	1	0	3	5				S2
03/29/1940	2	27	18	19	22	17	9	20	12	12	6	12	23	16	23	14	16	15	19	12	16	9	8	3	6	11	2	6	1				
03/18/1907	13	10	3	8	9	7	6	9	6	20	13	4	2	0	4	6	2	3	13	7	10	10	10	5	8	3	0	1					
01/10/1937	3	7	9	10	11	10	9	15	17	24	8	2	0	1	1	15	6	7	5	7	1	2	8	6	8	6	3	3					
12/27/1941	8	0	2	0	0	5	2	0	6	24	0	1	0	0	0	23	6	0	8	17	26	25	7	3	17	13	10	3					
12/19/1952	3	2	1	4	0	4	5	7	11	6	2	5	3	25	30	26	3	0	0	1	41	19	0	0	0	0	1	11					
No (P>20)	0	2	2	0	1	1	2	2	3	2	2	1	4	1	3	4	3	3	3	3	5	1	1	0	0	1	1	0	2	1	0	0	

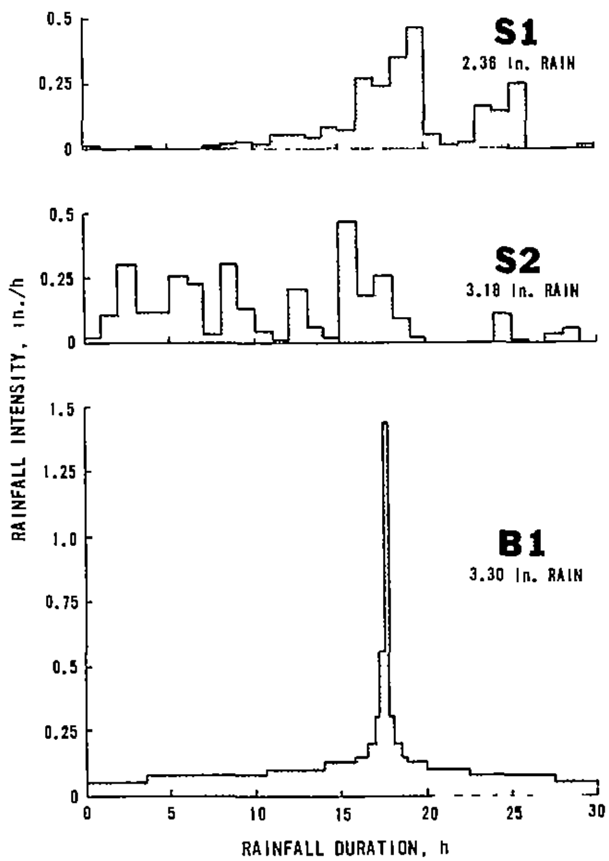

Figure 4-8. Design storm hyetographs.

8. To complete the modified Boston synthetic hyetograph procedure [35, Appendix A]:

   a. Locate the point in time where the maximum rainfall intensity will occur. Because of the great variety of rainfall distributions at the study area (Table 4-5), the average distribution method [35, Appendix A, Step 4] did not give definitive results. Instead, the maximum intensity was located by inspecting the distribution of the top 10% of the hourly rainfall intensities, in this case those greater than 0.20 in./h. From Table 4-5, bottom line, select hour 18 (the middle of a cluster).

   b. Determine from the U.S. Weather Bureau rainfall frequency atlas [36] the rainfall depths at the basin location for various durations and for a 1 year return period (Assumption 2), by interpolating between isopluvial lines. Compute the 5, 10, and 15 minute duration rainfalls from the 30 minute duration rainfall using the appropriate ratios [36, Table 3]. Rank the distribution of rainfalls by intervals, as follows:

Duration	Precipitation, in.	Interval	Remaining precipitation, in.	Interval intensity, in./h
5 min	0.185	First 5 min	0.185	2.22
10 min	0.285	Next 5 min	0.100	1.20
15 min	0.36	Next 5 min	0.075	0.90
30 min	0.50	Next 15 min	0.14	0.56
1 h	0.65	Next 30 min	0.15	0.30
2 h	0.85	Next 1 h	0.20	0.20
3 h	1.0	Next 1 h	0.15	0.15
6 h	1 4	Next 3 h	0.4	0.13
12 h	2.0	Next 6 h	0.6	0.10
24 h	3.0	Next 12 h	1.0	0.08
>24 h	--	Next 6 h	--	~0.05

   Note: The interval intensities must steadily decrease. To achieve this it may be necessary to slightly adjust the interpolated precipitation data.

   c. Select a time-step size, Δt. For subsequent simulation with the SWMM model (Example Problem 4-8), choose $\Delta t \approx$ duration/100. Therefore

$$\Delta t \approx \frac{30\ \text{h}}{100} = 18\ \text{min}$$

$$\Delta t = 15\ \text{min, say}$$

   d. Distribute the precipitation from Step 8b, by time-step (Step 8c), throughout the storm duration in proportion to the total time preceding and following the peak. Start with the time-step containing the hyetograph peak. Convert the ordinates of the resulting graph to rainfall intensity, to yield the design hyetograph. The resulting design hyetograph is labeled B1 in Figure 4-8.

<u>Comments</u>

1. The total precipitation in each of the three design storms is as follows:

   S1 2.36 in.
   S2 3.18 in.
   B1 3.30 in.

   Except for the short, intense peak, the synthetic storm B1 is more uniform than the others.

2. The great variety of totally different storm patterns which occur along the West Coast (Table 4-5) requires that a number of different design storm patterns be used for model calibration there.

3. Rainfall analysis methods obviously must depend on the nature of the data, and hence the study area location.

4. A good alternative to the above design storm approach is described in an EPA report [2] released after the completion of this study. It is based on a continuous characterization in terms of the percentage of the total annual precipitation volume and/or storms which could be treated.

EXAMPLE PROBLEM 4-5: INITIAL ASSESSMENT OF THE MANAGEMENT PROBLEM (METCALF & EDDY CONTINUOUS SIMULATION METHOD, SIMPLIFIED SWMM MODEL [9])

Determine the monthly average wet-weather flows and pollutant loads from the basin for two selected years for (a) separate storm sewers and (b) assuming the area is served by combined sewers.

Specified Conditions

1. Rainfall years. 1969-1970, 1970-1971

2. Rainfall amounts: Daily rainfall increments at San Jose City Hall, increased by 40% (direct extrapolation by isohyetal lines)

3. Average annual runoff quantity and quality characteristics, by land use:

   a. Separate sewers:

LAND USE	AREA ACRES	K-FACTOR	POLLUTANT CONCENTRATION IN SURFACE RUNOFF, MG/L					
			BOD	SS	VSS	TOT N	TOT P	OTHERS
RESIDENTIAL	3431.	0.27	10.40	211.50	123.00	1.70	0.44	0.0
RESIDENTIAL MULTI	0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMMERCIAL	1333.	0.50	41.50	288.10	181.70	3.84	0.98	0.0
INDUSTRIAL	154.	0.60	15.80	377.60	186.80	3.58	0.91	0.0
OPEN	4127.	0.23	0.20	5.00	4.80	0.11	0.02	0.0
AGRICULTURAL	0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0

   b. Combined sewers:

LAND USE	AREA ACRES	K-FACTOR	POLLUTANT CONCENTRATION IN SURFACE RUNOFF, MG/L					
			BOD	SS	VSS	TOT N	TOT P	OTHERS
RESIDENTIAL	3431.	0.27	42.70	871.90	505.70	7.01	1.80	0.0
RESIDENTIAL MULTI	0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMMERCIAL	1333.	0.50	171.30	1191.20	751.30	15.83	4.05	0.0
INDUSTRIAL	154.	0.60	64.90	1557.00	770.80	14.82	3.78	0.0
OPEN	4127.	0.23	0.90	20.40	19.90	0.46	0.08	0.0
AGRICULTURAL	0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note 1. The different runoff coefficients (K-factors) represent variations in perviousness with land use; the values used here had been previously calibrated by adjusting quantity and quality predictions for selected storms.

Note 2: The pollutant concentrations [9, Appendix D] are derived from the same source as those of Example Problem 4-1. The population density function, f , to adjust pollution concentrations from residential areas, was found to be 1.0, based on the basin's developed population density of 12.25 people/acre (72 947 people/[9045-3114] acres).

Assumptions

1. The average annual runoff is a prescribed fraction of the annual precipitation; this fraction varies only with type of land use.

2. Pollutant loads are determined by prescribed runoff concentrations [9, Table D-2].

Solution

1. Prepare input for the Simplified SWMM computer program, from the data listed under Specified Conditions.

2 Execute the program (0 01 min CPU time, $0.45 total cost, on IBM 370/168).

3. Computer output is presented in Table 4-6.

TABLE 4-6. COMPUTER OUTPUT FOR EXAMPLE PROBLEM 4-5

a. Separate sewers

YEAR 1969-1970 MONTHLY SUMMARY

MONTH	DAY	RAIN IN	RAIN DAYS	RUNOFF Mgal	OVERFLOW Mgal	TREATED Mgal	OVERFL DAYS	TREAT DAYS	MAX STORAGE Mgal	POLLUTANT LOAD, THOUSANDS OF POUNDS BOD	SS	VSS	TOT N	TOT P	OTHERS
7	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
8	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
9	30	0.20	1	14.0	14.0	0.0	1	0.0	0.0	2.	19.	11.	0.	0.	0.
10	31	0.87	5	62.1	62.1	0.0	5	0.0	0.0	8.	84.	51.	1.	0.	0.
11	30	1.30	3	93.1	93.1	0.0	3	0.0	0.0	11.	126.	76.	1.	0.	0.
12	31	2.20	10	157.2	157.2	0.0	10	0.0	0.0	19.	213.	128.	2.	1.	0.
1	31	5.63	15	402.6	402.6	0.0	15	0.0	0.0	50.	545.	328.	6.	1.	0.
2	28	2.14	9	153.2	153.2	0.0	9	0.0	0.0	19.	208.	125.	2.	1.	0.
3	31	3.05	5	218.3	218.3	0.0	5	0.0	0.0	27.	296.	178.	3.	1.	0.
4	30	0.29	3	21.0	21.0	0.0	3	0.0	0.0	3.	28.	17.	0.	0.	0.
5	31	0.03	1	2.0	2.0	0.0	1	0.0	0.0	0.	3.	2.	0.	0.	0.
6	30	0.14	1	10.0	10.0	0.0	1	0.0	0.0	1.	14.	8.	0.	0.	0.
YEARLY		15.85	53	1133.8	1133.8	0.0	53	0.0	0.0	140.	1536.	922.	16.	4.	0.

YEAR 1970-1971 MONTHLY SUMMARY

MONTH	DAY	RAIN IN.	RAIN DAYS	RUNOFF Mgal	OVERFLOW Mgal	TREATED Mgal	OVERFL DAYS	TREAT DAYS	MAX STORAGE Mgal	POLLUTANT LOAD, THOUSANDS OF POUNDS BOD	SS	VSS	TOT N	TOT P	OTHERS
7	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
8	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
9	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
10	31	0.49	3	35.1	35.1	0.0	3	0.0	0.0	4.	47.	29.	1.	0.	0.
11	30	8.71	12	623.0	623.0	0.0	12	0.0	0.0	77.	844.	507.	9.	2.	0.
12	31	5.45	15	389.6	389.6	0.0	15	0.0	0.0	48.	528.	317.	6.	1.	0.
1	31	1.27	8	91.1	91.1	0.0	8	0.0	0.0	11.	123.	74.	1.	0.	0.
2	28	0.76	4	54.1	54.1	0.0	4	0.0	0.0	7.	73.	44.	1.	0.	0.
3	31	2.18	6	156.2	156.2	0.0	6	0.0	0.0	19.	212.	127.	2.	1.	0.
4	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
5	31	0.11	5	8.0	8.0	0.0	5	0.0	0.0	1.	11.	7.	0.	0.	0.
6	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
YEARLY		18.97	53	1357.1	1357.1	0.0	53	0.0	0.0	167.	1838.	1104.	20.	5.	0.

b. Combined sewers

YEAR 1969-1970 MONTHLY SUMMARY

MONTH	DAY	RAIN IN	RAIN DAYS	RUNOFF Mgal	OVERFLOW Mgal	TREATED Mgal	OVERFL DAYS	TREAT DAYS	MAX STORAGE Mgal	POLLUTANT LOAD, THOUSANDS OF POUNDS BOD	SS	VSS	TOT N	TOT P	OTHERS
7	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
8	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
9	30	0.20	1	14.0	14.0	0.0	1	0.0	0.0	7.	78.	47.	1.	0.	0.
10	31	0.87	5	62.1	62.1	0.0	5	0.0	0.0	32.	347.	208.	4.	1.	0.
11	30	1.30	3	93.1	93.1	0.0	3	0.0	0.0	47.	521.	313.	5.	1.	0.
12	31	2.20	10	157.2	157.2	0.0	10	0.0	0.0	80.	879.	528.	9.	2.	0.
1	31	5.63	15	402.6	402.6	0.0	15	0.0	0.0	205.	2251.	1351.	23.	6.	0.
2	28	2.14	9	153.2	153.2	0.0	9	0.0	0.0	78.	857.	514.	9.	2.	0.
3	31	3.05	5	218.3	218.3	0.0	5	0.0	0.0	111.	1221.	733.	12.	3.	0.
4	30	0.29	3	21.0	21.0	0.0	3	0.0	0.0	11.	118.	71.	1.	0.	0.
5	31	0.03	1	2.0	2.0	0.0	1	0.0	0.0	1.	11.	7.	0.	0.	0.
6	30	0.14	1	10.0	10.0	0.0	1	0.0	0.0	5.	56.	34.	1.	0.	0.
YEARLY		15.85	53	1133.8	1133.8	0.0	53	0.0	0.0	577.	6338.	3804.	64.	17.	0.

Table 4-6. (Concluded)

YEAR 1970-1971						MONTHLY SUMMARY										
										POLLUTANT LOAD, THOUSANDS OF POUNDS						
MONTH	DAY	RAIN IN	RAIN DAYS	RUNOFF Mgal	OVERFLOW Mgal	TREATED Mgal	OVERFL DAYS	TREAT DAYS	MAX STORAGE Mgal	BOD	SS	VSS	TOT N	TOT P	OTHERS
7	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
8	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
9	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
10	31	0.49	3	35.1	35.1	0.0	3	0.0	0.0	18.	196.	118.	2.	1.	0.
11	30	8.71	12	623.0	623.0	0.0	12	0.0	0.0	317.	3483.	2090.	35.	9.	0.
12	31	5.45	15	389.6	389.6	0.0	15	0.0	0.0	198.	2178.	1307.	22.	6.	0.
1	31	1.27	8	91.1	91.1	0.0	8	0.0	0.0	46.	510.	306.	5.	1.	0.
2	28	0.76	4	54.1	54.1	0.0	4	0.0	0.0	28.	302.	181.	3.	1.	0.
3	31	2.18	6	156.2	156.2	0.0	6	0.0	0.0	79.	873.	524.	9.	2.	0.
4	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
5	31	0.11	5	8.0	8.0	0.0	5	0.0	0.0	4.	45.	27.	0.	0.	0.
6	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
YEARLY		18.97	53	1357.1	1357.1	0.0	53	0.0	0.0	690.	7587.	4554.	77.	21.	0.

Comments

1. The average annual basin runoff coefficient is 0.29 (2491 Mgal/34.82 in.).

2. The probable magnitude of the monthly and annual loads of significant wet-weather pollutants are listed in Table 4-6, for both (a) separate storm sewers and (b) combined sewers.

3. The annual wet-weather BOD load will be about 153 000 lb (separate sewers) or 633 000 lb (combined sewers), of which 71% originates from commercial land use areas and 25% from residential areas.

4. The average annual BOD concentration is 14.8 mg/L (separate sewers) or 61.0 mg/L (combined sewers).

5. These BOD loads and concentrations are greater than the results of Example Problem 4-1 for the following reasons:

   - This example yields a higher overall runoff coefficient
   - In particular, the runoff coefficient for commercial land use areas, which have by far the highest washoff BOD concentration, is notably larger in this example
   - Pollutant washoff is reduced in Example Problem 4-1 by 30% through the incorporation of a street sweeping effectiveness factor

EXAMPLE PROBLEM 4-6: PRELIMINARY PLANNING OF INTEGRATED STORAGE AND TREATMENT (METCALF & EDDY CONTINUOUS SIMULATION METHOD, SIMPLIFIED SWMM MODEL [9])

Determine the variation of storage capacities and costs required to yield various levels of BOD removal and overflow control with treatment capacities of (a) one-half dry-weather flow, and (b) four dry-weather flows.

Specified Conditions

1. Rainfall period: 1951-1976 (25 years)

2. Rainfall amounts: Daily rainfall increments at San Jose City Hall, increased by 40% (direct extrapolation by isohyetal lines).

3. Drainage basin served by separate sewers only.

4. Average annual runoff quantity and quality characteristics are the same as for Example Problem 4-5, Specified Condition 3a.

Assumptions

1. The average annual runoff is a prescribed fraction of the annual precipitation; this fraction varies only with type of land use.

2. Pollutant loads are determined by prescribed runoff concentrations [9, Table D-2].

3. Quantities passing through storage and treatment are determined from daily time-step computations.

4. One dry-weather flow equals 7.3 Mgal/d (Example Problem 4-3, Step 5a).

5. Representative annual cost (debt service plus operation and maintenance) of storage = $0.01626/gal·yr (Example Problem 4-3, Step 3).

6. Stormwater treatment removes 85% of each pollutant. Resulting treated effluent concentrations (using Specified Condition 4) are:

	mg/L
BOD	2.22
SS	24.35
VSS	14.63
Total N	1.73
Total P	0.07

Solution

1. Prepare input for the Simplified SWMM computer program, from the data listed under Specified Conditions and Assumption 6, plus the following treatment and storage capacities (Assumption 4):

Treatment (withdrawal) rate, Mgal/d	Storage capacity, Mgal	Treatment (withdrawal) rate, Mgal/d	Storage capacity, Mgal
3.6	0.0	29.2	0.0
3.6	2.0	29.2	2.0
3.6	5.0	29.2	5.0
3.6	20.0	29.2	20.0
3.6	50.0	29.2	50.0

2. Execute the program (0.44 min CPU time, $14.00 total cost, on IBM 370/168).

3. Sample computer output is presented in Table 4-7.

TABLE 4-7. SAMPLE COMPUTER OUTPUT FOR 2.0 Mgal STORAGE AND 3.6 Mgal/d TREATMENT CAPACITY

YEAR 1970 - 1971 MONTHLY SUMMARY

CALABAZAS CREEK SEPARATE-STOR/TREAT

MONTH	DAY	RAIN IN	RAIN DAYS	RUNOFF Mgal	OVERFLOW Mgal	TREATED Mgal	OVERFL DAYS	TREAT DAYS	MAX STORAGE Mgal	POLLUTANT LOAD, THOUSANDS OF POUNDS BOD	SS	VSS	TOT N	TOT P	OTHERS
7	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
8	31	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
9	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
10	31	0.49	3	35.1	20.3	14.8	2	4.1	2.0	3.	30.	18.	1.	0.	0.
11	30	8.71	12	623.0	577.4	43.6	11	12.1	2.0	72.	791.	475.	9.	2.	0.
12	31	5.45	15	389.6	333.4	58.2	12	16.2	2.0	42.	463.	278.	6.	1.	0.
1	31	1.27	8	91.1	66.1	25 0	5	6.9	2.0	9.	95.	57.	1.	0.	0.
2	28	0.76	4	54.1	34.3	19.8	3	5.5	2.0	5.	50.	30.	1.	0.	0.
3	31	2 18	6	156.2	128.6	27.6	5	7.7	2.0	16.	180.	108.	2.	0.	0.
4	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
5	31	0.11	5	8.0	0.0	8.0	0	2.2	0.0	0.	2.	1.	0.	0.	0.
6	30	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.	0.	0.	0.	0.	0.
YEARLY		18.97	53	1357.1	1160.1	197.0	38	64.7	2.0	147.	1611.	968.	20.	4.	0.

4. Calculate 25 year BOD removal efficiencies and storage costs (Assumption 5) from the average annual flows:

Storage capacity, Mgal	Treatment rate, Mgal/d	Overflow, Mgal/yr	Treated, Mgal/yr	Overflows, No.	BOD Released, 1000 lb/yr	BOD Removed, 1000 lb/yr	BOD Removed, %	Annual storage cost, $10^6/yr
0	0	1346	0	1359	166.0	0	0	0
0	3.6	1175	171	1021	148.1	17.9	10.8	0
2	3.6	1132	214	961	143.6	22.4	13.5	0.033
5	3.6	1081	265	883	138.2	27.8	16.7	0.081
20	3.6	940	406	721	123.5	42.5	25.6	0.325
50	3.6	802	544	609	109.0	57.0	34.3	0.813
0	29.2	546	800	377	82.1	83.9	50.5	0
2	29.2	524	822	355	79.9	86.1	51.9	0.033
5	29.2	495	851	331	76.8	89.2	53.7	0.081
20	29.2	370	976	263	63.7	102.3	61.6	0.325
50	29.2	217	1129	144	47.7	118.3	71.3	0.813

These results are presented graphically in Figures 4-9 and 4-10.

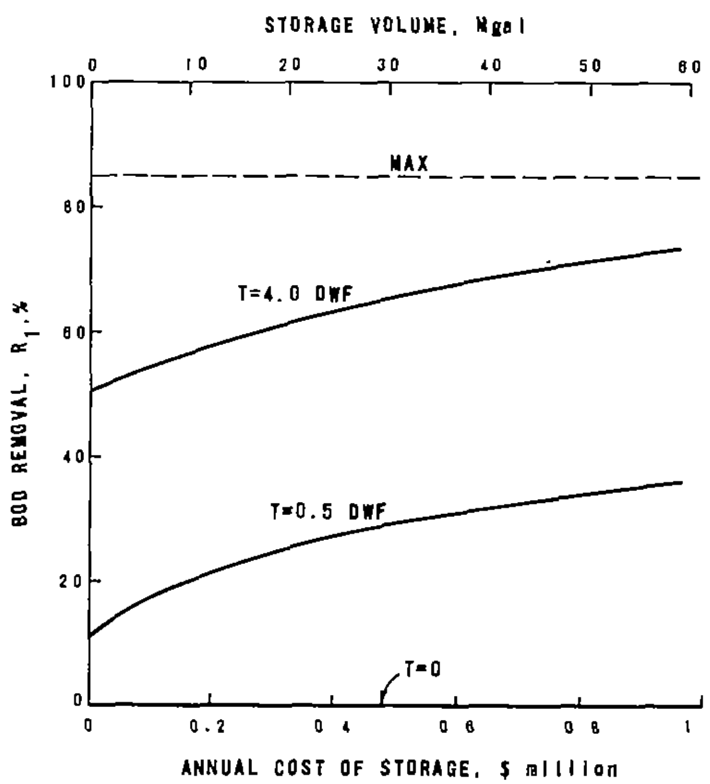

Figure 4-9. Variation of 1951-1976 BOD removal efficiencies with size and cost of storage.

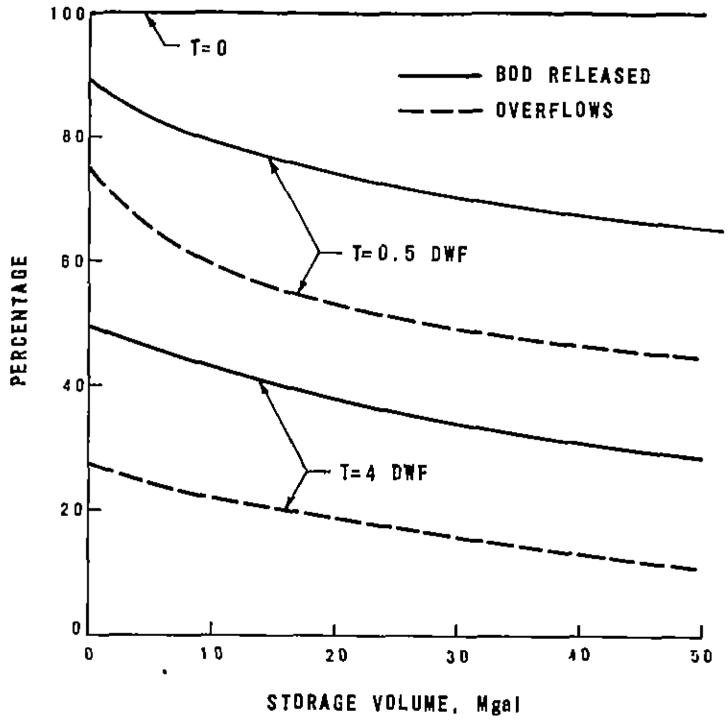

Figure 4-10. Variation of BOD releases and number of overflows during 1951-1976 with storage volume.

Comments

1. Increases in BOD removal are seen in Figure 4-9 to be relatively small for large increases in storage cost. The incremental benefits diminish with increasing storage cost.

2. The number of overflow (extreme) events that occur during the 25 year period is seen in Figure 4-10 to be reduced by storage and treatment far more significantly than is total BOD release.

3. The simplifying assumptions do not account for: (1) treatment accomplished in storage and (2) variability of treatment performance with the number and duration of treatment periods, startup effects, and mixing in storage. Consideration of these points through in-depth analysis may show improved storage benefits.

4. The inability of the Simplified SWMM model to simulate flow variations within each day (Assumption 3) suggests that overflows sufficiently short to not be modeled will somewhat reduce the BOD removals. It appears that this reduction might decrease with increasing storage volume.

EXAMPLE PROBLEM 4-7: CALIBRATE DETAILED EVENT MODEL ON THE TEST AREA (EPA SWMM MODEL [7, 28])

Adjust model parameters so that it predicts runoff quantities and qualities in good agreement with observations of two selected storms.

Specified Conditions

1. Storm dates (with outflow quantity and quality measurements):
   a. December 29-30, 1976
   b. January 2, 1977

2. Rainfall amounts and locations: 15 minute rainfall increments, recorded to the nearest 0.01 in., at a number of county rain gages surrounding the basin.

3. Drainage basin served by separate sewers only.

Solution

1. Divide the basin into subcatchments that correspond to the drainage network, so that each subarea has near-uniform land use and topography characteristics. Resulting study basin subcatchments are depicted in Figure 4-11 (see also Figure 13).

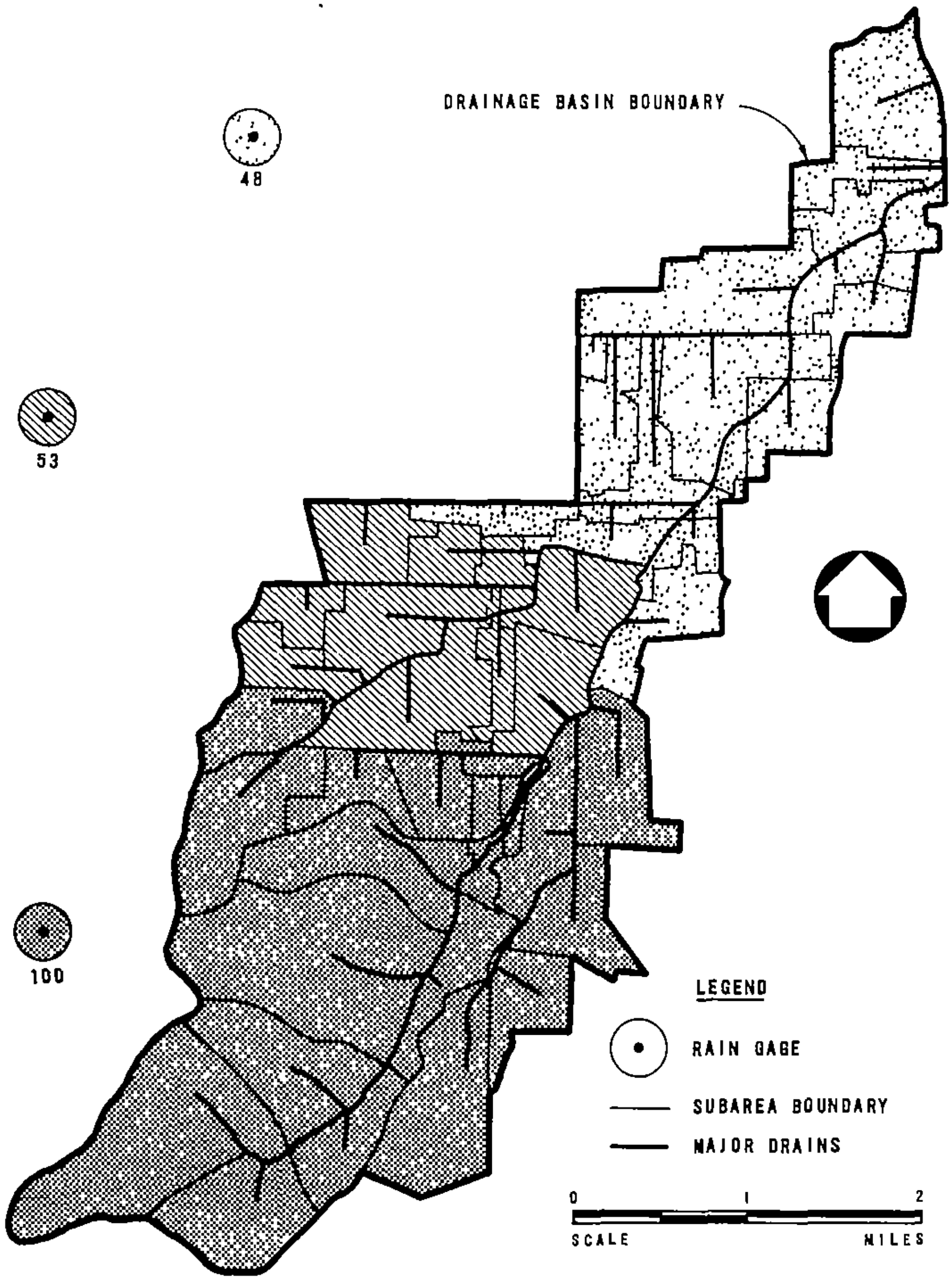

Figure 4-11. Subcatchments, drainage network, and rainfall allocations for SWMM simulation.

2. Prepare input data for the runoff block of the EPA SWMM computer program.

   Data were obtained from the following sources:

   - Topography maps
   - Zoning maps
   - Sewer and street maps
   - County channel cross-section and profile drawings
   - Aerial photographs
   - Municipality street cleaning records
   - Rain gage location maps
   - County rainfall records

   Numerical input data for each storm were prepared for the following:

   a. For the full basin:

      - Storm timing, time-step size, time since the previous storm
      - Rainfall (three gages)
      - Fraction of the impervious area with zero detention
      - Street cleaning data
      - Parameters to control computer output format

   b. For each subcatchment

      - Outlet location, area, width, slope, percent imperviousness, roughnesses, surface retention storages, infiltration parameters
      - Land use
      - Soil erosion parameters
      - Channel, pipe, and gutter geometries, roughnesses, lengths, and slopes

3. Gather for each storm the following prototype output data for calibration and verification purposes:

   - County streamflow records at the basin outlet (stream gage)
   - Water quality data from the analysis of grab samples, collected at the outlet stream gage throughout the storm for BOD, suspended solids, and numerous other constituents

4. Execute the uncalibrated computer program. IBM 370/168 computer requirements per storm were:

	CPU time, min	Total cost, $
Compile and execute	0.50	20.00
Compile only	0.25	--
Execute only	--	7.00

   The computed (uncalibrated) outflow hydrograph for the December storm, resulting from the application of the rain gage Station 100 rainfall to the entire basin, is compared with the observed prototype behavior in Figure 4-12.

5. Calibrate the model. This involves adjusting the estimated and uncertain model parameters, and making successive computer runs, until a set of parameters is found that minimizes the total error in both the quantity and quality simulations for all design storms.

   The computed outflow hydrographs and pollutographs of both design storms were modified to match the observed behavior as closely as possible by making the following model parameter adjustments:

   - Reduce imperviousness to about 70% of their uncalibrated values
   - Apply rainfall measured at three different gages (Stations 48, 53, and 100--see Figure 4-12 for hyetographs) to three segments of the basin, as defined by the Thiessen method (see shading in Figure 4-11).
   - Reduce fraction of impervious area that is directly connected from 20% to 1%
   - Reduce the erosion control practice factor, to reduce erosion
   - Adjust the various quality constituent ratios (percentages of suspended solids)

   The resulting computed (calibrated) outflow hydrograph for the December storm is compared with the observed and uncalibrated hydrographs in Figure 4-12 .

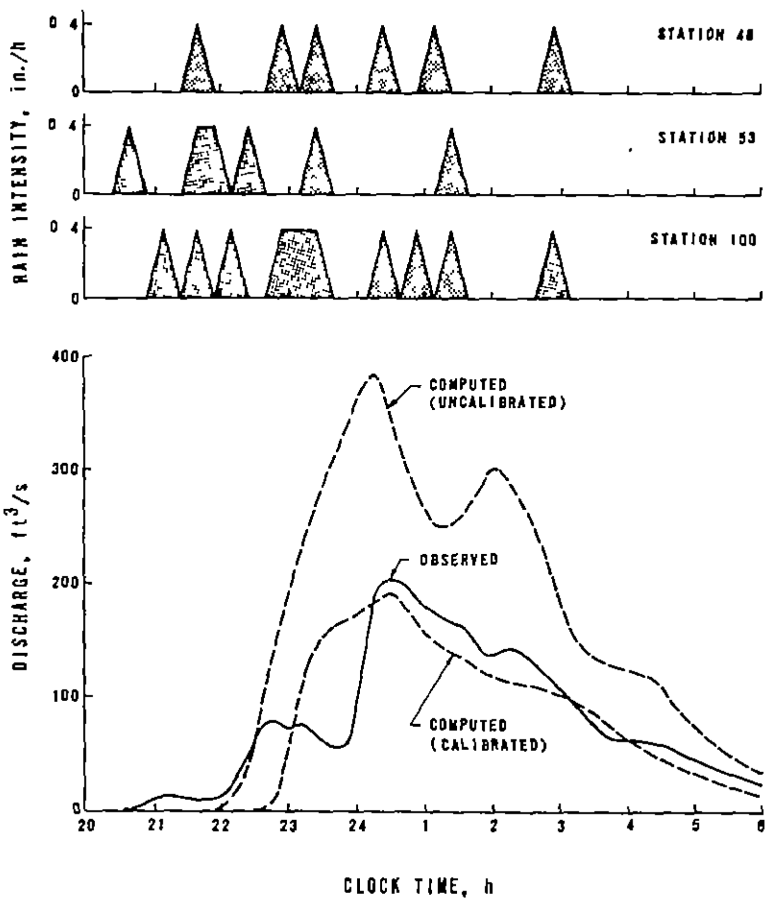

Figure 4-12. Observed rainfall and runoff, and computed runoff hydrographs, for the storm of December 29-30, 1976.

Comments

After completing calibration, as described above, the model must be verified with an additional different storm (or storms).

Note that the 1976-1977 water year storms were selected for technique demonstration only. These storms, occurring in a second consecutive drought year, exhibited abnormally high infiltration-percolation characteristics necessitating the high imperviousness reduction. Cross calibration with normal and wet years would also be required before selecting representative long-term parameter values.

EXAMPLE PROBLEM 4-8: SIZE A STORAGE BASIN FOR THE TEST AREA (EPA SWMM MODEL [7, 28])

Using the synthetic design storm (B1) selected in Example Problem 4-4, determine the storage capacity required to limit BOD released to 50% of the untreated value for this 1 year event. Check the effect of this storage on the other design storms (S1 and S2).

Specified Conditions

1. 15 minute rainfall increments, recorded to the nearest 0.01 in., are defined for the three design storm hyetographs by Figure 4-8.

2. Drainage basin served by separate sewers only.

Assumptions

1. Catchment conditions are the same as those prevailing during the SWMM calibration storms of Example Problem 4-7.

2. The design storms rain uniformly over the entire basin.

3. The storage basin is located at the basin outlet (Figures 4-4, 4-11), separated from the drainage system of Example Problem 4-7 by only a single manhole.

4. The storage basin has a geometric shape, with vertical sides. Outflow is by gravity over a 40 ft long fixed weir at the 10 ft depth level. At the start of the storm the unit is empty.

5. The type of flow within the storage basin is "plug flow" (as opposed to completely mixed). Maximum pollutant removals by sedimentation within storage are: SS 70%, BOD 38.5%, with a decay rate of 0.2/h.

6. Treatment capacity of 1 DWF, or 7.3 Mgal/d (Example Problem 4-3, Step 5a), is available, with secondary treatment efficiency (85% BOD removal).

7. Storage unit sludge is resuspended and ultimately delivered with other trapped solids to the dry-weather treatment plant.

Solution

1. Prepare input data for the Runoff Block of the EPA SWMM computer program. Use the same catchment data as those for the calibrated model of Example Problem 4-7 (Assumption 1). Prepare input rainfall hyetograph data for the uniform application (Assumption 2) of the three design storms of Example Problem 4-4 (Specified Condition 1).

2. Execute the runoff program three times, once for each design storm. IBM 370/168 computer requirements per storm were:

	CPU time, min	Cost, $
Compile	0.25	9.00
Execute	0.75	13.00

   Save the three output files.

3. Prepare input data for the Transport Block of the EPA SWMM computer program. In this case, this consists of specifying only a single manhole (Assumption 3)--the Transport Block is needed to link the Runoff and Storage blocks. Use the quantity and quality output from Runoff (Step 2) as input to Transport.

4. Execute the transport program three times, once for each design storm. IBM 370/168 computer requirements per storm were:

	CPU time, min	Cost, $
Compile	0.40	15.00
Execute	0.04	2.00

5. Select two initial trial storage volumes intended to bracket that which provides a 50% removal efficiency on the B1 design storm.

The total storm BOD load is 9428 lb, from Transport, and its total runoff volume is 95.1 Mgal. About 10 Mgal (7.3 Mgal/d x 1.5 d) will be treated directly, with 85% removal (Assumption 6). The flows simulated by storage/treatment are illustrated in Figure 4-13. With 42.6 Mgal storage capacity (50% of the remaining runoff volume), 85% removal of the trapped BOD and an estimated 30% BOD removal from the overflow by sedimentation (Assumption 5) yields 60% overall BOD removal. Therefore, select 20 and 50 Mgal as initial trial storage volumes.

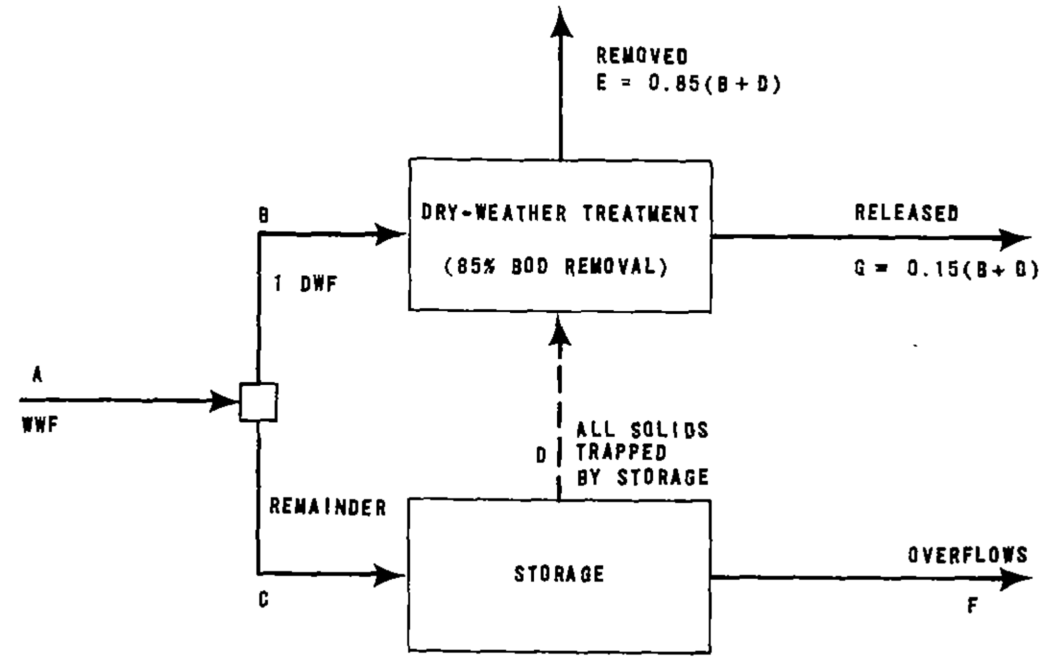

Figure 4-13. Schematic of flows simulated by storage/treatment.

6. Prepare input data for the Storage/Treatment Block of the EPA SWMM computer program. Specify external, in-line storage and treatment with the characteristics prescribed by Assumptions 4 through 6. Specify the base area, computing it from the (assumed) storage volume with a 10 ft sidewater depth. Suppress cost computations. Use the quantity and quality output from Transport (Step 4) as input to Storage/Treatment.

7. Execute the storage/treatment program for each of the storage capacities selected in Step 5, with quantity/quality input from Transport corresponding to the B1 design storm. Computer requirements per run were:

	CPU time, min	Cost, $
Compile	0.40	17.00
Execute	0.04	3.00

8. Compute the BOD releases, as indicated in Figure 4-13 (BOD release = F+G). The zero storage (treatment only) result may also be computed from the Step 7 runs. Plot the results on a graph (heavy dots in Figure 4-14). From this graph, estimate the storage volume that will limit BOD releases from the B1 storm to 50% (4714 lb). Rerun the storage/treatment program to verify this estimate, and repeat as necessary (more heavy dots on Figure 4-14). Result of the two additional trials: 40 Mgal storage capacity limits releases to 4798 lb BOD (50.9%, close enough).

9. Execute the storage/treatment program twice more, with the same 40 Mgal storage capacity, for the input quantity and quality from Transport corresponding to the S1 and S2 design storms. Compute the BOD releases for these two storms in the same manner as in Step 8. The results are compared with the B1 design storm results in Table 4-8.

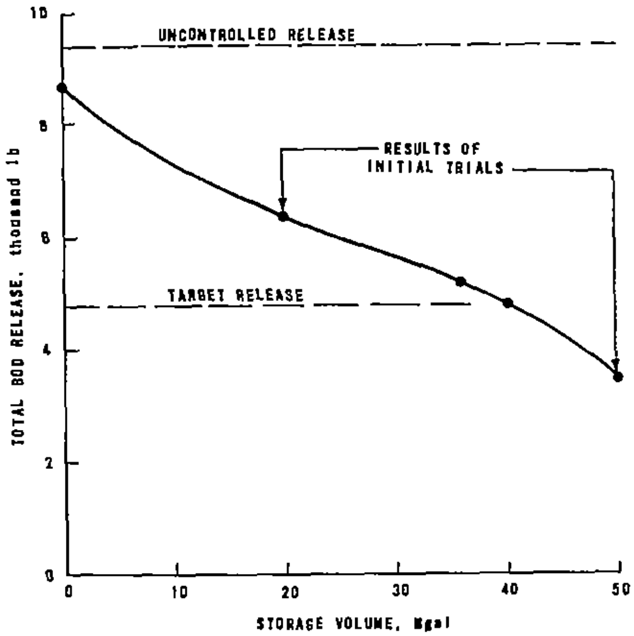

Figure 4-14. Effect of storage volume of BOD discharge of the B1 design storm.

TABLE 4-8. COMPARISON OF BOD RELEASES FROM THREE DESIGN STORMS AS COMPUTED BY SWMM WITH 40 Mgal STORAGE CAPACITY

		Design storm		
		B1	S1	S2
Total precipitation, in.		3.30	2.36	3.18
37.5 hour runoff, in.		0.39	0.29	0.40
BOD inflows, lb				
To treatment	(B)[a]	845	622	730
To storage	(C)	8583	7378	8660
Total	(A)	9428 (100%)	8000 (100%)	9390 (100%)
BOD captured, lb				
By storage	(D)	4602	4901	4954
BOD removals, lb				
Direct treatment	(0.85B)	718	529	621
Treated from storage	(0.85D)	3912	4166	4211
Total	(E)	4630 (49.1%)	4695 (58.7%)	4832 (51.5%)
BOD releases, lb				
Direct treatment	(0.15B)	127	93	109
Treated from storage	(0.15D)	690	735	743
Storage overflow	(F)	3981	1260	3183
Total	(F + G)	4798 (50.9%)	2088 (41.3%)	4035 (48.5%)

a. Refers to flow paths of Figure 4-13.

Comments

1. The low computed runoffs in Table 4-8 (all about 12% of total precipitation) result from the SWMM Runoff Block having been calibrated on storms occurring during an unusually dry winter (Example Problem 4-7).

2. Although the total precipitation of design storm B1 (3.30 in.) is greater than that of S2 (3.18 in.), its runoff is less (0.39 in. versus 0.40 in.). This is due to the differences in rainfall time distribution; with the exception of the brief peak, B1 is far more uniform (Figure 4-8).

3. While a 40 Mgal storage basin would take 5.5 days to pump out and process after the storm through the 7.3 Mgal/d treatment plant, this is deemed acceptable since the design storm magnitude was selected to occur only once a year.

4. The far higher peak of design storm B1 (Figure 4-8) has a significant effect on water quality. High rainfall intensities cause high erosion and scour, resulting in high suspended solids concentrations.

5. The SWMM Storage/Treatment Block computes sedimentation within storage only from that stormwater which overflows. Therefore, the effectiveness of the storage unit as a settling basin cannot be compared with its total capturing capability.

6. The strong impact of the chosen design storm on the required storage capacity, or the BOD removal, is evident from Table 4-8. With constant storage capacity, the BOD removal increases as the storm precipitation decreases.

EXAMPLE PROBLEM 4-9. TEST THE STORAGE BASIN SIZED BY SWMM WITH A LONG HISTORICAL RECORD (METCALF & EDDY CONTINUOUS SIMULATION METHOD, SIMPLIFIED SWMM MODEL [9])

Determine the annual number of overflows, and the pollutant loads discharged, which occur with the storage basin as sized in Example Problem 4-8, over a defined historical record.

Specified Conditions

1. Rainfall period: 1951-1976 (25 years; same as Example Problem 4-6).

2. Rainfall amounts: Daily rainfall increments at San Jose City Hall, increased by 40% (direct extrapolation by isohyetal lines).

3. Drainage basin is served by separate sewers only.

4. Average annual runoff quantity and quality characteristics are the same as those for Example Problem 4-5, Specified Condition 3a, with the exception of the K-factors. These are reduced to 41.4% of the values used in Example Problem 4-5, to reduce the overall runoff coefficient (previously 0.29) to that obtained with SWMM in Example Problem 4-8 (0.12).

Assumptions

1. Same assumptions are made as Assumptions 1 through 3 of Example Problem 4-6.

2. Treatment capacity of one dry-weather flow, or 7.3 Mgal/d, is available (as in Example Problems 4-3, 4-6, 4-8).

3. Treatment removes 85% of each stormwater pollutant; resulting treated effluent concentrations are as per Example Problem 4-6, Assumption 6.

4. Storage basin capacity is 40 Mgal (as sized in Example Problem 4-8).

5. Sedimentation in storage removes 30% of the BOD from overflows (compare with Example Problem 4-8, Assumption 5: 38.5% BOD removal, maximum). Eighty-five percent of the BOD in stormwater captured by storage is removed by subsequent treatment.

Solution

1. Prepare input for the Simplified SWMM computer program, from the data prescribed by the Specified Conditions and Assumption 3, plus the following treatment and storage capacities (Assumptions 2 and 4):

Treatment (withdrawal rate), Mgal/d	Storage capacity, Mgal
0.0	0
7.3	40

2. Execute the program twice, once for each storage/treatment combination. IBM 370/168 computer requirements (execute only) per run were: 0.05 min CPU time, $1.70 total cost.

3. Results for the storage-with-treatment run are summarized in Table 4-9. The uncontrolled release run (zero storage, zero treatment) yielded the following results:

Average annual overflow:	566.2 Mgal
Average annual BOD release:	69 280 lb
Average annual overflow days*:	54.5

TABLE 4-9. SUMMARY RESULT FOR 25 YEARS PERFORMANCE WITH 40 Mgal STORAGE AND 7.3 Mgal/d TREATMENT CAPACITY

CALABAZAS CREEK SEPARATE SEWERS									POLLUTANT LOAD, THOUSANDS OF POUNDS					
WATER YEAR	RAIN IN	RAIN DAYS	RUNOFF	OVERFLOW Mgal	TREATED Mgal	OVERFL DAYS*	TREAT DAYS	MAX STORAGE Mgal	BOD	SS	VSS	TOT N	TOT P	OTHERS
1951	27.34	68	823.1	177.6	645.4	11	88.4	40.0	34.	368.	221.	12.	1.	0.
1952	13.47	56	405.4	2.8	402.6	2	55.2	40.0	8.	86.	51.	6.	0.	0.
1953	14.11	48	424.8	11.3	413.5	5	56.6	40.0	9.	99.	60.	6.	0.	0.
1954	16.59	43	499.4	23.6	475.8	3	65.2	40.0	12.	128	77.	7.	0.	0.
1955	25.33	64	762.4	198.4	564.0	6	77.3	40.0	35.	379	228.	11.	1.	0.
1956	14.06	58	423.1	10.8	412.4	2	56.5	40.0	9.	98.	59.	6.	0.	0.
1957	30.67	75	923.4	183.9	739.5	17	101.3	40.0	36.	395.	238.	13.	1.	0.
1958	13.68	37	411.8	89.5	322.2	9	44.1	40.0	17.	185.	111.	6.	1.	0.
1959	14.57	43	438.7	57.5	381.2	5	52.2	40.0	14.	154.	93.	6.	0.	0
1960	13.85	56	416.8	3.6	413.2	2	56.6	40.0	8.	89.	53.	6.	0.	0
1961	17.67	45	531.9	140.1	391.8	9	53.7	40.0	24.	266.	160.	6.	1.	0.
1962	23.31	33	701.7	274.9	426.8	8	58.5	40.0	41.	453.	272.	10.	1.	0.
1963	14.24	41	428.6	60.6	368.0	4	50.4	40.0	14.	156.	94.	6.	0	0.
1964	21.17	63	637.2	102.2	535.0	12	73.3	40.0	22.	245.	147.	9.	1.	0.
1965	10.32	33	310.6	21.9	288.7	3	39.6	40.0	8.	88.	53.	4	0.	0.
1966	27.71	65	834.0	163.5	670.6	10	91.9	40.0	32	354.	213	12.	1.	0.
1967	18.40	50	553.8	127.1	426.7	2	58.4	40.0	23	256	154	8.	1	0.
1968	29.57	50	890.1	190.8	699.3	14	95.8	40.0	36.	396	238.	13.	1.	0
1969	15.85	53	477.1	47.9	429.2	5	58.8	40.0	14.	151	91.	7.	0.	0
1970	18.97	53	571.1	152.6	418.5	6	57.3	40.0	26.	288.	173.	8.	1.	0.
1971	8.93	41	268.9	3.3	265.6	2	36.4	40.0	5.	58.	35.	4	0.	0
1972	32.69	80	984.1	213.4	770.6	16	105.6	40.0	40.	441.	265.	14	1.	0
1973	22.62	72	681.1	14.8	666.2	2	91.3	40.0	14.	155	93.	10	0.	0.
1974	17.05	55	513.3	24.3	489.0	4	67.0	40.0	12	132.	79.	7.	0.	0.
1975	8.06	41	243.2	0.0	243.2	0	33.3	27.4	5	49.	30	4.	0	0.
TOTAL				2296.4		159			498					
AVERAGE				91.86		6.4			19.92					

*Days with some overflow

4. Adjust computed BOD releases, since Simplified SWMM makes no allowance for sedimentation within storage.

   BOD concentration entering storage (Assumption 3)

   = 2.22 mg/L/0.15
   = 14.8 mg/L (ppm)

   Average annual BOD load removed by sedimentation from 91.86 Mgal/yr average storage overflow (Assumption 5)

   $= 0.3\ (91.86 \times 10^6\ \text{gal})\ 8.34\ \text{lb/gal}\ (14.8 \times 10^{-6})$
   = 3402 lb

   Corrected average annual BOD release (Table 4-9)

   = 19 920 - 3402
   = 16 518 lb

5. Compute corrected 25 year BOD removal efficiency

Uncontrolled BOD release	= 69 280 lb/yr (Step 3)
Controlled BOD release	= 16 518 lb/yr (Step 4)
BOD removal	= 52 762 lb/yr
	= 76.2%

Comments

1 Given the stated assumptions, the 40 Mgal storage basin, combined with 1 DWF treatment capacity, reduces the number of overflows by 88% (6.4 versus 54.4 days), and removes 76% of the BOD load, over the long term. This latter figure compares with a 49% BOD removal for the 1 year design storm event (Example Problem 4-8, Table 4-8), and is 90% of the defined optimal treatment efficiency (85%).

There are two primary observations that may be made from the foregoing series of examples:

1. The range of applications for which such models may be used is very broad.

2. The capabilities of the models in their original forms to be able to serve the required purposes are notably limited in most cases.

The tremendous range of possible model applications has only been hinted at by these example problems.

While the models are of great help, they usually only partially fulfill the task requirements. Often, additions or modifications must be patched in; these are easier to effect in the more flexible desktop models, but they are presently less complete and tested. Model results usually must be interpreted and often adapted. All these considerations, together with the more fundamental question of model applicability, serve to underscore the need for appropriately qualified and experienced professionals to oversee usage.

Further, more specific observations that may be made about the preceding Example Problems are:

- The URS desktop procedure of Example Problem 4-2 requires much tedious hand computation, and for the amount of effort involved offers low accuracy by comparison with a detail event model such as SWMM.

- While a detailed event model provides excellent detail (Example Problem 4-8), it requires a significant investment in prior calibration (Example Problem 4-7).

- The simplified, continuous simulation models offer relatively high benefits for low costs and effort (Example Problems 4-5 and 4-6). They make possible good inexpensive assessments of the long-term impacts of designs (Example Problem 4-9).

- The economic procedures (Example Problem 4-3) are untested in applications. They need a fair testing period, with further shakedown and evolution. They appear to be particularly sensitive to unit costs, which should be investigated further.

- The selection of design storms (Example Problem 4-4) can be a tricky business, with significant consequences Some standardization of procedures for the various prevailing conditions would be desirable.

SECTION 5

STORMWATER CHARACTERISTICS - DATA BASE AND NORMALIZATION

In order to address a stormwater runoff or combined sewer overflow problem, an investigator must have knowledge of the characteristics of the problem. This section presents an overview of four areas that are integral to the solution of urban runoff problems.

1. Sources of Stormwater Pollutants. Stormwater pollutants are materials washed from the air and the land surface during rainfall or snowmelt events. It is reasonable to assume that some land surface activities, uses, and characteristics will cause greater pollutant loading than others. Known causal relations will be examined and quantified if possible. An understanding of sources allows some estimation of loadings, pinpoints areas that require in-depth survey, and provides the basis for developing nonstructural control alternatives.

2. Discharge Characteristics. Data gathered from several studies of stormwater runoff and combined sewer overflow are presented as a guide to what can be expected at the "end of the pipe." The information gives the investigator a starting point with which to compare stormwater pollutants to other sources within a basin and evaluate site specific data for its applicability.

3. Residuals. Solids derived from stormwater treatment must be considered in developing a complete pollution abatement program. It is necessary to evaluate the anticipated quantities and characteristics in order to provide for the final disposal of the treatment sludges.

4. Receiving Water Impacts. The goal of any stormwater study is the mitigation or prevention of adverse impacts on the receiving water. Summaries of studies of stormwater pollution impacts will be presented. The data indicate the potential adverse effects and some approaches to the evaluation of impact.

SOURCES OF STORMWATER POLLUTANTS

An understanding of the potential sources of stormwater pollutants is of primary importance when studying the impact of urban runoff. The accumulation of the various pollutants within a basin can be attributed to several sources and the individual effects are difficult to separate. However, a qualitative knowledge of the probable sources enables an investigator to concentrate on expected problem areas and evaluate source controls that could be used to curtail an adverse pollutant loading before it reaches the sewer system. The principal sources of runoff pollutants are as follows [1]:

1. Street pavement. The components of road surface degradation can become part of the urban runoff loading. The aggregate material is the largest contributor and additional quantities will come from the binder, fillers, and any substance applied to the surface. The amount of pollutants will depend on the age and type of surface, the climate, and the quantity and type of traffic.

2. Motor vehicles. Vehicles can contribute a wide variety of materials to the street surface runoff. Fuels and lubricants spill or leak, particles are worn from tires or brake linings, exhaust emissions collect on the road surface, and corrosion products or broken parts fall from vehicles. While the quantity of material deposited by motor vehicles is expected to be relatively small, the pollution potential is important. Vehicles are the principal nonpoint source of asbestos and some heavy metals including lead.

3. Atmospheric fallout. Air pollutants include dust, contaminants, and particles from industrial stacks and vents, from automobiles and planes, and from exposed land. The airborne matter will settle on the land surface and washoff as contaminated runoff. The potential significance of dustfall was indicated during a study done in Cincinnati [2]. During the study period 567 kg/ha (506 lb/acre) of dustfall were measured at a monitoring station and 818 kg/ha (730 lb/acre) of suspended solids were measured in storm runoff.

4. Vegetation. Leaves, grass, clippings, and other plant materials that fall or are deposited on urban land will become part of the runoff problem. Quantities will depend on the geographic location, season, landscaping practices, and disposal methods.

5. Land surface. The type of ground cover found in a drainage basin and the amount of vehicular and pedestrian traffic is a function of land use and will affect the quality of storm runoff.

6. Litter. Litter consists of various kinds of discarded refuse items, packaging material, and animal droppings. Although the quantities are small and not significant sources of pollution, the debris is highly visible in a receiving stream and can be a focal point for citizen complaints.

7. Spills. These obvious surface contaminants can include almost any substance hauled over city streets. Dirt, sand, and gravel are the most common examples. Industrial and chemical spills are potentially the most serious.

8. Anti-skid compounds and chemicals. Cold weather cities employ large amounts of substances designed to melt ice during the winter. Salts, sand, and ash are the commonly used agents. A variety of other chemicals may be used as fertilizers, pesticides, and

herbicides. Most of these materials will become part of the urban runoff.

9. Construction sites. Soil erosion from land disturbed by construction is a highly visible source of solids in storm runoff. Important urban sites will include large scale projects such as highway construction and urban renewal. The construction methods and control measures will influence quantities.

10. Collection network. Storm sewer networks using natural or improved earthen channels will be subject to erosion of the banks. Collection networks also tend to accumulate deposits of material that will be dislodged and transported by storm flows.

It is obvious from this list that there are many potential sources of pollutants within each basin and the sources vary in importance. The quantities that accumulate are a function of natural conditions and urban development. Most of the sources exist concurrently in the urban environment and, although their effects cannot be isolated, some relative quantities are discussed in the following sections.

Street Pavement

Several studies of pavement wear in Germany [3] have indicated that at least 0.05 cm (0.02 in.) of surface will be worn from a tire lane during a summer. Assuming four tire lanes each 1 m (3 ft) wide in a 7.5 m (24 ft) road, this wear would amount to 0.66 kg/m^2 (0.13 lb/ft^2) of road per summer. The wear in the winter can be considerably greater if studded snow tires are used by a large portion of the cars. The effect is shown in Table 10 for northern and southern Germany; the southern locations are in the Alps region where 30 to 40% of the cars use studded tires.

TABLE 10. ABRASION OF ASPHALT-CONCRETE HIGHWAY SURFACES IN WINTER AND SUMMER

Site	Vehicles per 24 hours	Abrasion, in.	
		Summer	Winter
Northern Germany	7 500	0.01-0.03	0 02-0.04
	4 500	0.004-0.01	0.02
Southern Germany	5 000	0.02-0.03	0.06-0.07
	9 000	0.02-0.04	0.07-0 10
	13 000	0.02	0.23-0.26

in x 2.54 = cm

Motor Vehicles

A detailed study of street surface pollutants in Washington, D.C., found that most of the contaminants were traffic related [4]. This does not mean that the pollutants necessarily originate with the vehicle itself but rather that the expected loading intensity can be expressed in the form:

$$Y = B + mX \qquad (5\text{-}1)$$

where Y = loading intensity, kg/mi (lb/mi)
B = amount of pollutant unrelated to traffic, kg/mi (lb/mi)
m = traffic related deposition rate, kg/axle·km (lb/axle·mi)
X = traffic in axles.

The values of m, deposition rate, for traffic related contaminants are shown in Table 11. Depositions of orthophosphate, fecal coliforms, fecal streptococci, cadmium, PCBs, and litter were not considered to be traffic related. The values of B for both asbestos and lead were negative, indicating that these important pollutants are entirely traffic related.

TABLE 11. DEPOSITION RATES OF TRAFFIC-RELATED ROADWAY MATERIAL [4]

Parameter	Units	Deposition rate
Dry weight	lb/1000 axle-mi	2.38
Volume	qt/1000 axle-mi	0.63
Volatile solids	lb/1000 axle-mi	0.12
BOD		5.43×10^{-3}
COD		0.13
Grease		1.52×10^{-2}
Total phosphate - P		1.44×10^{-3}
Nitrate - N		1.89×10^{-4}
Nitrite - N		2.26×10^{-5}
Kjeldahl - N		3.72×10^{-4}
Chloride		2.20×10^{-3}
Petroleum		8.52×10^{-3}
n-paraffins	lb/1000 axle-mi	5.99×10^{-3}
Asbestos	fibers/axle-mi	$3.86 \times 10^{+5}$
Rubber	lb/1000 axle-mi	1.24×10^{-2}
Lead		2.79×10^{-2}
Chromium		1.85×10^{-4}
Copper		2.84×10^{-4}
Nickel		4.40×10^{-4}
Zinc		3.50×10^{-3}
Magnetic fraction	lb/1000 axle-mi	0.13

lb/1000 axle-mi x 0.28 = kg/1000 axle-km
qt/1000 axle-mi x 0.59 = L/1000 axle-km

Although only a small fraction of the traffic related deposits come directly from vehicles, it is an important fraction. Grease, petroleum, lead, zinc, copper, nickel, chromium, and asbestos are all potentially toxic to aquatic life and all originate directly from vehicles. The remaining traffic related organics, nutrients, and solids are products of road surface abrasion or have been carried to the roadway by vehicular action.

The values for pollutant deposition shown in Table 11 were developed by sweeping and washing sections of street at 24 hour intervals. Additional samples, taken to compute accumulation of material for a 3 day interval, showed that accumulation is not a linear function of the deposition rate. The Washington, D.C., work showed that roadway accumulation levels off in about 4 days due to traffic related removal mechanisms. Although dust and dirt are blown onto adjacent land surfaces by vehicle movement and other means, at least a portion of the displaced material is still available for transport by storm runoff.

A calculation of tire wear in a German study [3] indicates that the weight loss per tire is 12% or 0.9 kg (2 lb) over a lifespan of 30 000 km (20 000 mi). Therefore, the potential deposition rate for four tire vehicles is 0.12 kg/km (0.4 lb/mi) per 1 000 vehicles. The tire rubber consists of 87% carbon, 6% hydrogen, 2% sulfur, and 2% zinc oxide.

Vegetation

Waste vegetative matter is an important source of organic and nutrient pollutants in urban stormwater. The quantity of leaves, grasses, seeds, and clippings will depend upon the particular urban area and public works practices. Vegetative waste will become part of the urban runoff when material falls or is dumped onto impervious areas and when pollutants are leached from decaying organic matter.

Typical concentrations of nutrients in vegetative litter are shown in Table 12.

TABLE 12. NUTRIENTS IN VEGETATIVE LITTER [5]
Percentage, dry weight

	Nitrogen	Phosphorus	Potassium	Ash
Evergreen leaves	0.58-1.25	0.04-0.10	0.12-0.39	3.01-4.33
Deciduous leaves	0.51-1 01	0.09-0.28	0.40-1.18	5 71-15.16

Studies of quantities of waste vegetative matter have generally been performed by scientists interested in forest ecosystems. Consequently, quantitative estimates deal with full canopy situations. Estimates for urban areas should be modified to account for lower tree densities; quantitative estimates are presented in Table 13.

TABLE 13. VEGETATIVE LITTER PRODUCTION [6]
lb/acre·yr

Source	Yield of waste matter
Evergreens[a]	3300
Deciduous trees[a]	2854
Rye grass[b]	3675-5612

a. Full canopy.

b. Florida.

lb/acre·yr x 1.121 = kg/ha·yr

Land Surface

General land use categories are an important basis for studying stormwater pollution because of the relation between land use and many specific sources. For example, there is usually less dustfall in a residential-commercial area than in an industrial zone and there is heavier motor vehicle traffic in a commercial-industrial area than in residential neighborhoods. In this sense, evaluation of pollutants versus surface use will include two hard to quantify sources--litter and spills.

Three major research studies have documented the effects of land use on the accumulation of pollutants in urban areas [4, 7, 8]. While the reports are not directly comparable with each other because of different collection and analyzing techniques, they show the relative influence of land use. A summary of the studies is shown in Table 14.

The specific pollutants found in urban runoff will be affected also by the different categories of land use. The differences are shown in Table 15.

The data in Tables 14 and 15 were obtained by sweeping, vacuuming, or washing pollutants from street surfaces in urban areas with the specific land use noted. The areas sampled were small enough to be a valid indication of the differences in pollutant accumulation for general land uses. However, the dry street surface samples do not necessarily represent the portion that will wash off during a runoff event and do not include pollutant loadings from areas other than streets.

Anti-Skid Compounds and Chemicals

It is difficult to quantify chemicals that are a source of stormwater pollutants because of great variations in application rates. A few ranges can be presented as an indication of the potential magnitude of the problem.

Salt application for deicing can be a serious source of chlorides in runoff; ranges of application rates are shown in Table 16.

TABLE 14. DUST AND DIRT ACCUMULATION RATES FOR DIFFERENT LAND USES

	Single family	Multi-family	Commercial	Industrial
APWA at Chicago [7]				
Mean, lb/curb-mi·d	37	121	174	284
Median, lb/curb-mi·d	18	90	143	111
Number of samples	60	93	126	46
Adjusted URS data at several cities [8]				
Mean, lb/curb-mi·d	155	107	46	292
Mean without extreme, lb/curb-mi·d	71	56	20	138
Median, lb/curb-mi·d	69	32	20	74
Number of samples	21	14	17	20
Biospherics at Washington, D.C., (shopping center only) [4]				
Mean, lb/curb-mi·d	...	...	62	...
Median, lb/curb-mi d	...	...	67	...
Number of samples	...	...	8	...
Overall mean, lb/curb-mi·d	45	110	150	240

lb/curb-mi·d x 0.28 = kg/curb km·d

Abrasives used on street surfaces will also become part of direct runoff or snowmelt runoff in proportion to the amount applied. Stockpiles of salt or abrasives may also be important point sources of pollutants.

The next most important source of chemicals is the application of fertilizers, insecticides, and herbicides. Although quantities are small, the enrichment or toxic effects make them important to runoff studies. In a multicity study performed in 1971, quantities of pesticides were measured in road dust. Presumably, this is material that will easily wash off into receiving waters during a runoff event; ranges are given in Table 17.

Construction Sites and Collection Networks

The principal mechanism of pollution from these two sources is erosion. Soil erosion is a major source of stormwater solids for urban and suburban areas. The problem areas are construction sites, undeveloped areas, highway cuts, urban renewal areas, and drainage ditches themselves. In addition to specific sources, general erosion will take place from all unpaved areas. Erosion is a function of a number of physical conditions, and it is difficult to predict an erosion quantity for a complete urban area; however, an understanding of the mechanism of erosion is important when considering potential management techniques.

TABLE 15. CONCENTRATIONS OF POLLUTANTS BY LAND USE CHARACTERISTICS [6]
ppm of Dry Solids Unless Otherwise Noted

Pollutant	Land use			
	Single family residential	Multifamily residential	Commercial	Industrial
BOD	5 260	3 370	7 190	2 920
COD	39 300	42 000	61 700	25 100
Total nitrogen	460	550	420	430
Soluble PO_4-P	16	19	20	8
Cadmium	3.3	2.7	2.9	3.6
Chromium	200	180	140	240
Copper	91	73	95	87
Iron	21 300	18 500	21 600	22 500
Manganese	450	340	380	430
Nickel	38	18	94	44
Lead	1 570	1 980	2 330	1 590
Strontium	32	19	17	13
Zinc	310	280	690	280
Fecal coliforms, No./g	82 500	388 000	36 900	30 700
Total coliforms, No./g	891 000	1 900 000	1 000 000	419 000

TABLE 16. SALT APPLICATION FOR DEICING [9]

Area	Application rate per snowday, lb/mi
Northeastern states	670-1 820
North-central states	10-1 840
Southern states	0-1 610
West-central states	110-550
Southwestern states	300-400
Western states	0-1 320

lb/mi x 0.28 = kg/km

TABLE 17. PESTICIDE LOADS FOUND IN SEVERAL CITIES [1]

Pesticide	Lb/curb-mi Range	Median value
Dieldrin	3-27	24
PCB	65-3 400	1 100
BP-DDD	0.5-120	67
Methoxychlor	0-8 500	.. ..
P, P-DDT	1-170	61
Endrin	0-2	.....
Methyl parathion	0-20	.....
Lindane	0-17	....
Total pesticides	136-11 910	1 420

lb/curb-mi x 0.28 = kg/curb-km

The Universal Soil Loss Equation is an empirical formula derived by the Agricultural Research Service to estimate average annual erosion from farm plots. Since it was statistically developed to estimate gross erosion from small areas over a period of years, it is more of a management tool than a predictive formula. The equation is:

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad (5\text{-}2)$$

where A = soil loss, mass/unit area
R = rainfall factor
K = soil erodibility factor
LS = slope length gradient factor
C = ground cover index factor
P = erosion control factor

The factor R accounts for rainfall energy and intensity, K considers the ease with which the particular soil can be eroded, and LS is a function of slope length and gradient. The factors C and P are the keys to the control of erosion since they are more easily modified than the other three factors. Both were empirically developed by assuming that loose, noncompacted soil with no cover represents C and P factors of 1.0. The use of cover material or erosion control practices will reduce the factors and the amount of soil loss. Representative values are shown in Tables 18 and 19.

Examples of typical erosion rates are shown in Table 20. The quantities indicate a substantial increase in erosion when land is developed for either agriculture or urbanization. The particularly heavy rates from construction activities point out the need to apply control technology to urban and highway construction sites.

TABLE 18. GROUND COVER FACTOR "C" [5]

Type of cover	C value
None	1.0
Permanent seeding	
First 60 days	0.40
60 days to 1 year	0.05
After 1 year	0.01
Sod	0.01
Hay or straw	
1.0 ton/acre	0.20
2.0 tons/acre	0.05
Stone or gravel	
15 tons/acre	0.80
60 tons/acre	0.20
Chemical mulch (90 days)	0.50
Woodchips	
2 tons/acre	0.80
7 tons/acre	0.20

tons/acre x 2240 = kg/ha

Summary

Many sources of stormwater pollutants are present in a basin and their effects interact and overlap. It is difficult to attribute the pollutants measured at the discharge from a basin to a specific source within the drainage area. The importance of this section is in understanding why there is a problem and why construction site erosion prevention should be practiced or why the drainage from a highway intersection should be diverted from a sensitive stream. Results of studies giving overall pollutant concentrations follow.

DISCHARGE CHARACTERISTICS

The investigation of stormwater discharges is concerned with two different types of polluted flows--separate stormwater runoff from storm sewers or drainage channels and combined sewer overflows from sewers containing both runoff and sanitary sewage. The sources of runoff contamination have been described in the preceding section and it is evident that surface runoff has the potential to transport a significant load of pollutants. In this section the results of several monitoring efforts will be presented to indicate the range of pollutant concentrations that can be expected. Some explanation of the individual studies is given to help the reader judge the applicability of the data to his particular problem.

TABLE 19. EROSION CONTROL FACTOR "P" [5]

Surface condition	P value
Loose as a disced plow layer	1.0
Compact, smooth, scraped up, and downhill	1.3
Compact, raked up, and downhill	1.2
Compact, smooth, scraped across slope	1.2
Compact, raked across slope	0.9
Rough, irregular surface	0.9
Loose with rough surface	0.8
Loose with smooth surface	0.9
Structures	
Sediment basin	
0.04 basin/acre	0.5
0.06 basin/acre	0.3
Downstream sediment basin	
With chemicals	0.1
Without chemicals	0.2

acre x 0.405 = ha

TABLE 20. EROSION RATES [5]

Sediment source	Erosion rate, tons/mi^2·yr	Geographic location	Comment
Natural	15-320		
Agricultural	200-70 000		
Urban	50,000	Kensington, Md.	Extensive construction
	1 000-100 000		Small urban construction area
	1 000	Washington, D.C.	750 mi^2 average
	500	Philadelphia, Pa.	
	146-2 300	Washington, D.C. watersheds	As urbanization increases
Highway construction	36 000	Fairfax Co., Va.	Construction on 179 acres
	50 000-150 000	Georgia	Cut slopes

tons/mi^2·yr x 3.5 = kg/ha·yr
mi^2 x 2.590 = km^2

Urban Stormwater Runoff

The quality of urban runoff has been investigated at several sites across the country. The techniques, methodology, and goals varied from project to project, but the combined results present a good indication of the concentrations of pollutants that can be expected in urban runoff. The results of several representative sampling efforts are shown in Table 21. The samples were taken in various parts of the country, from diverse land use, during different seasons, and during dissimilar rainfall events. The average pollutant concentrations shown in the table indicate an order of magnitude of the stormwater runoff problem and the ranges indicate the wide variations in concentrations that may be anticipated. The individual studies involved will show some of the relationships between runoff quality and land or storm characteristics.

TABLE 21. POLLUTANT CONCENTRATIONS IN STORMWATER RUNOFF

City	Average pollutant concentrations, mg/L									
	TSS	VSS	BOD	COD	Kjeldahl nitrogen	Total nitrogen	Phosphorus	OPO_4-P	Lead	Fecal coliforms[a]
Atlanta, Georgia [10]	287	...	9	48	0.57	0.82	0.33	....	0.15	6 300
Des Moines, Iowa [11]	419	104	56	...	2.09	3.19	0.56	0.15	....	......
Durham, North Carolina [12]	1 223	122	.	170	0.96	. .	0.82	....	0.46	230
Knoxville, Tennessee [13]	440	..	7	98	1.9	2.5	0.63	0.30	0.17	20 300
Oklahoma City, Oklahoma	147	...	22	116	2 08	3 22	1.00	1 00	0 24	40 000
Tulsa, Oklahoma [14]	367	..	12	86	0.85	..	....	0 38	....	420
Santa Clara, California	284	70	20	147	....	5 8	0.23	....	0.75	......
Pullach, Germany [3]	158	53	11	125	....	...	.. .	..	....	......
Average (not weighted)	415	88	20	113	1.41	3.11	0.62	0.46	0.35	13 500
Range	147-1 223	53-122	7-56	48-170	0.57-2 09	0.82-5.8	0.33-1.00	0.15-1 00	0.15-0 75	230-40 000

a. Organisms/100 mL

Atlanta, Georgia--

The purpose of the Atlanta study was to investigate the impact of urban runoff and combined sewer overflows on the Chattahoochee River, a major water supply and recreational river in the Southeast. Samples were taken from storm runoff at four suburban sites and one downtown location in order to calibrate the runoff model being used to estimate pollutant loading. The results of the sample analysis are shown in Table 22. The four suburban areas vary in land use characteristics as shown in Table 23.

It is difficult to draw detailed conclusions from the limited number of samples taken in Atlanta, but the authors listed some comparisons that may be valid indications of pollutional trends [10].

- The downtown sample is far more heavily polluted than the suburban samples. For most pollutant concentrations measured, the downtown sample is greater than any suburban sample.

- The suspended solids and COD concentrations increase as the percent of the basin that is developed increases.
- Increased lead concentrations appear to be linked with increased commercial land use; this is probably due to large traffic volumes in shopping areas.
- BOD, phosphorus, and total nitrogen did not appear to be related to land use.

TABLE 22. POLLUTANT CONCENTRATIONS IN STORMWATER RUNOFF, ATLANTA, GEORGIA [10]

Site	Pollutants							
	TSS	BOD	COD	Kjeldahl nitrogen	Total nitrogen	Phosphorus	Lead	Fecal coliforms[a]
Montreal Road								
Mean, mg/L	215	6	26	0.73	0.94	0.33	0.08	11 000
Parkside Circle								
Mean, mg/L	296	11	61	0.52	0.72	0.31	0.21	4 600
Plantation Lane								
Mean, mg/L	323	12	63	0.57	0.83	0.35	0.27	2 100
Drew Valley Road								
Mean, mg/L	428	9	71	0.53	0.91	0.35	0.13	6 500
Suburban Total								
Mean, mg/L	287	9	48	0.57	0.82	0.33	0.15	6 300
Range	1-1 989	0-42	5-164	0.25-1.06	0.38-1.51	0.01-1.28	0.05-0.8	10-104 000
No. of samples	63	60	60	13	8	60	59	53
Downtown sample	277	76	597	1.53	2.45	0.37	2.20	. ..

a. Organisms/100 mL.

TABLE 23. LAND USE CHARACTERISTICS, ATLANTA, GEORGIA

Site	Density people/acre	Land use, %			
		Residential	Commercial	Industrial	Open
Montreal Road	3.1	36	6	18	40
Parkside Circle	5.6	53	15	3	29
Plantation Lane	5.1	14	18	58	
Drew Valley Road	2.8	90	0	10	

people/acre x 2.47 = people/ha

Des Moines, Iowa--

The Des Moines study was an evaluation of potential solutions to stormwater runoff problems and included a sampling program to analyze the quality of combined sewer overflows, storm runoff, and the receiving waters. The pollutant concentrations found in runoff from three areas with separate sewer systems are shown in Table 24. The values indicate that there is very little difference in average quality between the three areas. The sampling program covered both winter and summer runoff conditions with snowmelt as well as direct runoff. A comparison of snowmelt runoff versus rainfall runoff is shown in Table 25. The data indicate that phosphorus is the only pollutant showing a significant effect due to the form of precipitation. The investigators in Des Moines also found that pollutant concentrations generally decreased with time during a storm and cumulative pollutant loading usually "ran ahead" of cumulative flow quantities. These patterns were attributed to a first flush effect in which loose surface material is suspended by the initial runoff water, making it more concentrated than runoff later in the storm.

TABLE 24. POLLUTANT CONCENTRATIONS IN STORMWATER RUNOFF, DES MOINES [11]
mg/L

Site	TSS	VSS	BOD	NH_3-N	Total nitrogen	PO_4-P	OPO_4-P	Comments
S-1, mean	315	99	48	1.99	3.10	0.41	0.06	7.4 people per acre, older residential with considerable park space
S-3, mean	578	101	63	1.60	3.07	0.33	0.14	5.3 people per acre; residential with considerable grassy area
0-11, mean	404	110	56	2.30	3.24	0.70	0.19	10.7 people per acre; considerable industrial and commercial
Summary								
Mean	419	104	56	2.09	3.19	0.56	0.15	
Range	9-3 170	6-484	12-166	0-27.8	0-29.7	0-3.92	0-2.36	
No. of samples	89	84	84	49	49	36	45	

acre x 0.405 = ha

TABLE 25. COMPARISON OF RUNOFF QUALITY FOR SNOWMELT VERSUS RAINFALL [1]

	Pollutants						
	TSS	VSS	BOD	NH_3-N	Total nitrogen	PO_4-P	OPO_4-P
Rainfall runoff							
Mean, mg/L	426	96	51	2.21	3.25	0.68	0.19
No. of samples	48	45	56	31	31	27	32
Snow melt runoff							
Mean, mg/L	411	113	65	1.89	3.08	0.22	0.04
No. of samples	41	39	28	18	18	9	13

Durham, North Carolina--

The Durham study was not designed to be as site specific as the previous two studies in that variables affecting runoff quality were analyzed to develop predictive equations. Although the data were based on samples from the Durham area, the form of equations and relationships between variables and loading should be applicable to other areas with similar climate and topography. Many pollutants were analyzed during the study and the mean values are shown in Table 26. Regression analysis was performed to relate pollutant loading to four variables considered to have important effects on runoff quality. The four variables were rate of runoff, time from storm start, time from last storm, and time from last peak. The first two variables dealing with the storm event were found to be the most influential and little correlation increase resulted from considering elapsed time between storms or peaks. The final regression equations are shown in Table 27; CFS is the runoff quantity in cubic feet per second and TFSS is the elapsed time from the storm start.

TABLE 26. POLLUTANT CONCENTRATIONS IN STORMWATER RUNOFF, DURHAM, NORTH CAROLINA [12]

Pollutant	Mean, mg/L	Range, mg/L	No of samples
COD	170	20-1 042	491
TOC	42	5.5-384	413
Total solids	1 440	194-8 620	325
Volatile solids	205	33-1 170	221
TSS	1 223	27-7 340	408
VSS	122	5-970	312
Kjeldahl nitrogen, N	0.96	0.1-11.6	313
Total phosphorus, P	0.82	0.2-16	310
Fecal coliforms (No./mL)	230	1-2 000	327
Aluminum	16	6-35.7	63
Calcium	4.8	1.1-31	180
Cobalt	0.16	0.04-0.47	145
Chromium	0.23	0.06-0.47	232
Copper	0.15	0.04-0.50	225
Iron	12	1.3-58.7	257
Lead	0.46	0.1-2.86	336
Magnesium	10	3.6-24	217
Manganese	0.67	0.12-3.2	244
Nickel	0.15	0.09-0.29	103
Zinc	0.36	0.09-4.6	310
Alkalinity	56	24-124	80
BOD[a]	60	2-320	208

a. The authors feel that BOD results were affected by changing dilutions in the laboratory and recommend that BOD not be considered an appropriate measure of pollutant strength. (See p. 48, Reference [12] for the full discussion.)

TABLE 27. REGRESSION EQUATIONS RELATING POLLUTANT CONCENTRATION TO RUNOFF CHARACTERISTICS, DURHAM, NORTH CAROLINA [12]

Pollutant	Concentration, mg/L	
	As developed	Normalized
TSS	$222\ CFS^{0.23}\ TFSS^{-0.16}$	$1102\ R^{0.23}\ TFSS^{-0.16}$
VSS	$44\ CFS^{0.18}\ TFSS^{-0.17}$	$153\ R^{0.18}\ TFSS^{-0.17}$
COD	$113\ CFS^{0.11}\ TFSS^{-0.28}$	$242\ R^{0.11}\ TFSS^{-0.28}$
Kjeldahl nitrogen	$0.85\ CFS^{0.87}\ TFSS^{-0.29}$	$363\ R^{0.87}\ TFSS^{-0.29}$
Total phosphorus	$0.80\ CFS^{0.03}\ TFSS^{-0.29}$	$0.98\ R^{0.03}\ TFSS^{-0.29}$
Lead	$0.27\ CFS^{0.125}\ TFSS^{-0.29}$	$0.64\ R^{0.125}\ TFSS^{-0.29}$

Note: CFS = runoff, ft^3/s
TFSS = time from storm start, hours
R = runoff, in./h

$ft^3/s \times 0.028 = m^3/s$
in./h x 2.54 = cm/h

The quantity is necessarily dependent on the area of the Durham basin, 417 ha (1029 acres), and so the equations cannot be directly compared with results from other sites. In the second set of equations in Table 27, the equations have been normalized by converting cubic feet per second of runoff to inches per hour of runoff using the actual area of the basin. In most cases the pollutant concentrations increase with greater quantities of runoff, indicating increased erosion, pickup, and transport capacities of higher flows. The concentrations also tend to decrease as a storm event continues, indicating that the reservoir of pollutants on the land surface decreases or at least becomes more difficult to pick up and transport.

Knoxville, Tennessee--

The purpose of the Knoxville study was to investigate the effects of urbanization on an area of Tennessee that overlies a formation of soluble carbonate rock. The principal concern was that urbanization would greatly increase the impervious fraction of a basin and consequently cause increased runoff quantity with the associated pollutant loading. During the investigation, samples were taken from four urbanizing watersheds, upstream areas, and precipitation in an effort to determine probable impacts. The data obtained from the project watersheds are presented in Table 28. An interesting analysis made in Knoxville was the comparison of atmospheric input to a basin (dry fallout and precipitation) and output (streamflow); the analysis is shown in Table 29. Fourth Creek, First Creek, and Plantation Hills the streamflow is mostly storm runoff and it is shown that atmospheric sources are particularly important.

TABLE 28. POLLUTANT CONCENTRATIONS IN STORMWATER RUNOFF, KNOXVILLE, TENNESSEE [13]

Site	Pollutants, mg/L									
	TSS	BOD	COD	Kjeldahl nitrogen	NO_3-N	PO_4-P	OPO_4-P	Lead	Mercury	Fecal coliforms[a]
Fourth Creek, mean	1 200	12	110	2.4	0.7	1.1	0.20	0 34	0.0026	... . .
Third Creek, mean	240	9.1	95	1 5	0.6	0 49	0.26	0.13	0 0004	. . ..
First Creek, mean	150	6 3	32	0.65	0.6	0.56	0.46	0.13	0.0006	....
Plantation Hills, mean	46	2	29	1.0	0.4	0.36	0.32	0 08	0.0014	20 300
Total										
Mean	440	7 4	98	1.9	0.6	0 63	0 30	0 17	0 0017	20 300
Range	3-6 400	0-86	12-700	0.04-13	0 01-12	0 03-6 9	0 01-1 6	0-1.6	0 00005-0 047	670-700 000
No. of samples	175	181	70	76	177	183	176	189	76	40

Note: Fourth Creek - 0.82 acres, 45% impervious, commercial
Third Creek - 1 60 acres, 28% impervious, industrial-residential
First Creek - 0.5 acre, 16% impervious, residential.
Plantation Hills - 0 24 acre, 23% impervious, suburban.

a Organisms/100 mL

acre x 0 405 = ha

TABLE 29. COMPARISON OF WATERSHED LOADINGS, ATMOSPHERIC INPUT VERSUS RUNOFF OUTPUT, KNOXVILLE, TENNESSEE [13]

Site	Annual loading, lb/acre					
	TSS	COD	Kjeldahl nitrogen	NO_3-N	PO_4-P	Lead
Fourth Creek						
Atmospheric input	160	400	24	3,8	4.1	1.6
Runoff output	4 600	400	8	2.8	4.4	0.8
Third Creek						
Atmospheric input	250	670	19	8.0	3.2	0.5
Runoff output	980	510	8	5.0	3.8	0.9
First Creek						
Atmospheric input	120	430	18	3.5	1.3	0.5
Runoff output	80	30	1	1.2	1.1	0.2
Plantation Hills						
Atmospheric input	60	340	11	3.2	0.8	0.8
Runoff output	20	30	1	0 4	0.4	0 04

lb/acre x 1.12 = kg/ha

Tulsa, Oklahoma--

The Tulsa study was an investigation of storm runoff pollution as it relates to land activity and precipitation. Sampling points were set up for 15 test areas in Tulsa and regression analysis was used to relate pollutant loading to surface characteristics such as area, slope, population density, and land use or to precipitation variables such as intensity, total volume, time from start of storm and time from antecedent event. The pollutant concentrations found in the 15 areas are shown in Table 30 and the relationship between pollutants and significant variables is summarized graphically in Table 31. Some of the basic observations developed from this study include:

- The principal sources of pollutants are washoff from impervious area and erosion of drainage channels.
- Bacterial pollution can be related to the general sanitary condition of the sites.
- Pollutant concentrations decreased with time from the start of the storm and time from the antecedent event. Solids and bacteria increased with intensity of the storm.
- For residential areas, pollution increases with population density and degree of development.

TABLE 30. POLLUTANT CONCENTRATIONS IN STORMWATER RUNOFF, TULSA, OKLAHOMA [14]

Site No. and land use	Average value, mg/L					
	TSS	BOD	COD	Organic nitrogen	OPO_4-P	Fecal coliforms[a]
1. Light industrial	2052	13	110	1.11	1.14	0.94
2. Commercial	169	8	45	0.95	0.28	1 90
3. Residential	280	8	65	1.48	0.62	3.30
4. Industrial-residential	340	14	103	0.97	0.34	0.77
5. Residential	136	18	138	0.72	0.28	1.50
6. Industrial	195	12	90	0.65	0.28	18.00
7. Residential	84	8	48	0.80	0.22	0.12
8. Residential	240	15	115	0.69	0.38	0.45
9. Residential	260	10	117	0.67	0.33	0.29
10. Commercial	300	11	107	0.83	0.23	0.30
11. Residential-commercial	401	14	116	0.66	0.36	0.62
12. Airport	89	8	45	0.39	0.18	0.01
13. Residential	332	15	88	1.46	0.39	0.18
14. Golf course	445	11	53	0.96	0.32	0.37
15. Residential	183	12	42	0.36	0.26	0.35
Total						
Mean, mg/L	367	12	86	0.85	0.38	0.42
Range	0-6378	1-39	14-405	0-5.32	0-4.93	0-470
No. of samples	464	480	425	393	389	358

a. 1000 organisms/100 mL.

TABLE 31. PRECIPITATION AND LAND USE FACTORS AFFECTING POLLUTANT CONCENTRATIONS IN TULSA, OKLAHOMA

	Total solids	Suspended solids	BOD	COD	Organic nitrogen	Ortho-phosphate	Total coliforms	Fecal coliforms
Time from start of storm, h	0	X	●	●	X	X	●	0
Rain, in.	0	X	●	●	X	X	●	0
Intensity, in./h	●	X	●	0	X	X	0	0
Time from antecedent event, h	0	X	0	0	X	X	0	●
Amount of antecedent event, in.	0	X	●	0	X	X	●	0
Intensity of antecedent event, in./h	0	X	0	0	X	X	●	●
Area of basin, acres	●	0	0	0	0	0	0	0
Length of main stream, ft	0	0	●	0	0	0	0	0
Slope of drainage area, %	●	0	0	0	●	●	0	0
Environmental index	0	0	0	0	0	0	●	0
Covered storm sewers, mi	0	0	0	●	0	0	0	0
Arterial streets, %	●	●	●	0	●	0	0	0
Other streets, %	0	0	0	0	●	0	●	0
Residential density, people/acre	0	0	0	●	0	0	●	0
Industrial land, %	●	●	0	0	0	●	0	0
Unused land, %	●	●	0	0	0	●	0	0

Note: 0 no significant correlation
X not investigated
● significant correlation between factor and pollutant

in. x 2.54 = cm
acres x 0.405 = ha
ft x 0.305 = m
mi x 1.61 = km

Oklahoma City, Oklahoma, and Santa Clara County, California--

Data for two regional "Section 208" studies have been gathered. In both cases an effort was made to evaluate runoff from different land use classifications within the study area and compare the data for ultimate use in a planning process. Summaries of the results to date are shown in Table 32. The Oklahoma data clearly show the relatively high potential impact of a central urban core and indicate that pollution concentration increases with increasing population density. The Santa Clara samples also show that some parameters appear to be related to land use.